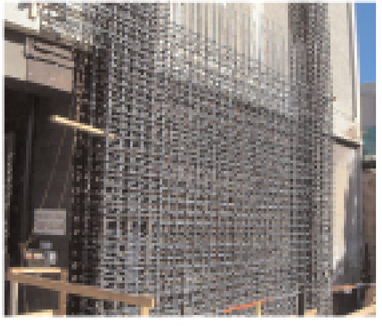
Bracing Berkeley

A Guide to Seismic Safety on the UC Berkeley Campus

Mary C. Comerio
Stephen Tobriner
Ariane Fehrenkamp



PEER 2006/01
Pacific Earthquake Engineering Research Center
College of Engineering
University of California, Berkeley
January 2006

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Contents

Acknowledgments

From fall 2000 through spring 2003, Professors Comerio and Tobriner of the Department of Architecture taught a special seminar course focused on the UC Berkeley seismic retrofit program. The students in the course were asked to do case studies of various buildings on the campus. This guide is a short summary of those student papers. We thank these students for their participation and studies of individual retrofit projects—without whom we could not have assembled this guide. The following students took part in the classes and provided some of the material used here.

Fall 2000: Tim Dunn, Jennifer Heebink, Janelle Hensley, Jonathan Man, William McCollum, Godwin Moy, Freddy Seen, Z. Smith, Kurt Wong.

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Introduction

Stephen Tobriner

Although the campus of the University of California, Berkeley has never been damaged by a major earthquake, it has undertaken one of the most comprehensive and costly seismic retrofit programs in history. After great earthquakes whole cities have been reconstructed and surviving buildings retrofitted, but at the University of California, Berkeley, it was the threat of future earthquakes that galvanized the administration, the faculty, and staff to act. As of the centennial of the 1906 earthquake, most of the hazardous buildings have been retrofitted or demolished and replaced with new buildings. The seismic program coordinated structural improvements with deferred maintenance to improve the quality of classrooms, libraries, and laboratories across the campus. In some cases, it was more economical and more programmatically appropriate to replace poor buildings with new facilities. The campus stands as an impressive monument to earthquake safety that will save thousands of lives when the expected magnitude 7-plus earthquake occurs.

The campus is now a museum of the most advanced seismic retrofit and construction strategies employed in the late twentieth and early twenty-first centuries, yet without a guide it is hard to understand what was done and why. Behind each seismic project there is a story that includes why a specific building was chosen, how the clients, the architects, and the engineers attempted to remedy the situation, and after much discussion, what technical solutions were chosen. Each building is a unique combination of multiple problems. Often the teams of engineers confronting those problems suggested different solutions. What is appropriate? Should the building inhabitants be relocated or should it be retrofitted while in use? What techniques are best? Base isolation? Deep pile foundations? Mat foundations? Strengthened concrete shear walls? An exterior steel moment frame with diagonal bracing? A new dual system? Unbonded braces? Concrete or steel jacketing? Nearly every method for reinforcement has been used on the campus.

This short guide to campus seismic projects provides a building case study for major projects with a technical explanation of the engineering problems encountered and the decisions involved in the final retrofit strategy. Additionally, some projects are documented in this guide but not fully described. It is our hope that with this guide in hand, interested architects, engineers, and lay people will make their way through the Berkeley campus and examine the major retrofit projects and newly designed buildings. The first two authors have been involved in the seismic program here and felt that its history should be preserved. To that end we have taught graduate seminars individually and jointly on the building retrofits as they were happening. The authors note that this guide includes many, but not all, of the campus seismic improvement projects. It is our pleasure to invite readers to explore the Berkeley campus with the eyes of engineers and to enter the world of earthquake safety by examining seismic solutions for individual structures while understanding the complexity of the institution of the University of California. The projects we describe are technical solutions to a societal problem, earthquake safety. Our attempt has been to integrate a discussion of engineering solutions with the factors peculiar to the problems of teaching, research, and housing at the University of California, Berkeley.

A Short History of Earthquake Mitigation at the University of California, Berkeley

Stephen Tobriner

From its inception as the site for the University of California, major earthquakes provided the stimulus for increased seismic safety at the Berkeley campus. In 1868, when the university was considering construction plans for its first building at Berkeley, a major earthquake damaged San Francisco and the East Bay. The magnitude 7.0 earthquake, with its epicenter on the East Bay's Hayward fault, was not only strong and destructive, but perilously close to the location of the new campus. Faculty members Professors O. P. Fitzgerald, Richard Hammond, Horatio Stebbins, and John W. Dwinelle, writing in 1868, cautioned about ignoring the danger:

> We publish pamphlets to demonstrate that earthquakes in California are not so destructive of human life as lightning and tempests are in the Atlantic States. But still, the historical fact is well established that earthquakes have occurred in California, which have caused a fearful destruction of life and property… We are of [the] opinion that we have no right to disregard these warnings that one of our first cares should be to make our buildings as safe as possible for the youths who may be confided to our charge…The building which we propose to erect for the purpose of instruction is to be filled three times a day, for eight months a year, with California youth and as we trust, with the flower of that youth, and to be occupied most of the time by the professors and their assistants. Any great calamity which should happen to a large portion of that youth on the site of the University would not only be a great calamity to the State and to the nation, but also create a great prejudice against the University itself.

Accordingly, the first building on the University of Calilfornia campus, South Hall (1870–1873), was designed to be seismically resistant. Eight years after the earthquake of 1906, the first major tower at the University, Sather Tower, was being designed by campus architect John Galen Howard. The 1914 tower was built to be not only pleasing aesthetically, but safe in earthquakes. The consulting engineer, Professor Charles Derleth, Jr., designed it to be flexible yet strong. Using the performance of buildings in San Francisco during the 1906 earthquakes as models, he tried to calculate the period and drift of the tower in relation to the expected ground motion of a future earthquake. While Sather Tower is a sophisticated example of earthquake awareness, the shorter structures built by John Galen Howard throughout the campus illustrate his misconception that well-built brick and steel-frame construction was earthquake safe—a judgement that would later prove costly for the University.

The 1925 Santa Barbara and the 1933 Long Beach earthquakes prompted campus safety surveys and a seismic retrofit proposal for Stephens Hall (built in 1921), the old Student Union. The first evidence of concern for campus safety is a report commissioned by the president of the university in 1923, and undertaken by Professor B. F. Raber, of the Mechanical Engineering Department, to evaluate wooden buildings on campus. Thirty buildings were listed and ranked "Poor," "Fair," and "Good." A year after the 1925 earthquake, B. M. Woods, another professor of mechanical engineering, identified a wooden building called "Mechanics Annex" as a seismic hazard. In a letter to Dean F. H. Probert of the College of Engineering the hazard is described:

> Wooden buildings on campus do not offer evident and certain promise of damage from tremors, with the exception of one. This is the so-called "Mechanics Annex"… This structure is (1) exceedingly light and poorly braced (2) very scantily nailed, (3) supported upon wooden footings for very light, long and poorly braced columns supporting the first floor, and (4) located in an undoubtedly precarious position on a steep hillside of comparatively loose earth.

The building was demolished as an "earthquake and fire hazard," perhaps the first earthquake mitigation of an existing building on the University of California campus. After the 1933 earthquake, a number of UC professors attempted to address seismic hazards on campus. Chief among them was Charles Derleth Jr., dean of the College of Engineering, who warned about the falling hazards constituted by the finials on Wheeler Hall or the poorly built partitions in several buildings. President Sproul formed the "Disaster Preparedness Committee" in 1933 which remained active through 1936. In a 1934 report each building on campus was surveyed and rated for its earthquake resistance, with Stephens Hall being the worst and Cowell Hospital (later demolished to build the Haas Business School) the best.

The charter of the university released it from meeting local or state building codes, so the Field Act, passed in 1933 by the State of California to upgrade school buildings for seismic safety did not apply. But the university was subject to the provisions of the Riley Act, (Title 24 of the California Administrative Code). This act placed the responsibility for seismic safety squarely on the administration as it does today.

The San Fernando earthquake of 1971 once again stimulated the university to reevaluate its building stock in relation to earthquake danger. By then the University of California had grown to include nine campuses. The earthquake had caused minor damage to buildings at the Los Angeles campus, 22 miles from the epicenter. The regents of the university became concerned and approved funds for a preliminary survey of all nine campuses. In 1975 the regents adopted the University of California Seismic Safety Policy. This was developed by engineer Frank McClure, of McClure and Messinger, Consulting Structural Engineers, from conclusions and recommendations of a special committee convened by Chancellor Albert Bowker of the Berkeley campus. The committee was called the “Chancellor's Seismic Review Committee,” and its original members were Professors Bruce A. Bolt, Ray W. Clough, Henry Lagorio, H. Bolton Seed, Karl V. Steinbrugge (chairman), and Elmo R. Morgan, director of facilities, Berkeley campus. Outside members included Henry J. Degenkolb and Michael V. Pregnoff, both distinguished structural engineers. This committee would become responsible for seismic safety on the Berkeley campus. Meanwhile, the President’s Office of the University of California engaged the firm, H. J. Degenkolb and Associates, in conjunction with Frank McClure, to carry out a survey of all university buildings in 1977 and 1978. A seismic performance rating of Good, Fair, Poor, or Very Poor was assigned to each building on the nine campuses, a tremendous job. The report was submitted to the university in 1978.

In the 1980s the Seismic Review Committee quietly worked at ensuring that current projects met seismic performance and code standards while attempting to bring the issue of seismic safety to the attention of the Chancellor of the Berkeley campus and to the university community. Professor Bolt, chairman of the committee, was perhaps the most vocal critic of the university's position during this period. The complex interrelationship between the university's monetary problems in fulfilling its goals as a leading institution of teaching and research had to be balanced with its charge to provide a safe environment for students, faculty, and staff.

The 1989 Loma Prieta earthquake, the 1994 Northridge earthquake in Southern California, and the 1995 Kobe earthquake in Japan refocused the university on seismic safety. With some retrofits already completed, university officials and California lawmakers saw what could happen after the tremendous losses in these events. The Hayward fault runs through the campus, making UC Berkeley one of the most seismically hazardous campuses in the world.

In the late 1990s, the university began in earnest to make the entire campus earthquake resistant in one of the most ambitious programs, not only in California but in the world. The university imaginatively combined grants from the Federal Emergency Management Agency (FEMA), funds from bond measures to higher education, and university money to kick off a new program known as the “Seismic Action Plan for Facilities Enhancement and Renewal” (SAFER). With the retrofits of four significant campus buildings, SAFER estimated that the university would need to invest $1 billion over twenty to thirty years to improve the seismic safety of campus facilities.

The next essay, by Mary Comerio, discusses the creation of SAFER and the Disaster Resistant University programs. The University of California, Berkeley, has a long history of attention to earthquake safety, and the current retrofit program is a model for seismic mitigation and risk management for all institutions worldwide.

The SAFER Program

The University of California, Berkeley, is a world-class institution. The campus includes approximately 33,000 students and more than 13,000 faculty and staff in over 100 academic departments and research units. The campus has 114 buildings on 177 acres, with about 5 million net square feet of classrooms, libraries, offices, research laboratories, and other specialized facilities. The campus has over 8 million square feet of built space in total. The annual campus operating budget exceeds $1 billion, and the 2004 sponsored research awards totaled $585 million.

After the 1971 San Fernando earthquake, building codes for new construction were made more stringent in 1976, and existing buildings deficiencies were recognized. In 1978, the UC system adopted a seismic safety policy, and Degenkolb Engineers undertook a seismic review of existing buildings on the Berkeley campus. This review led to a program of structural upgrades for key buildings such as University Hall, which then housed the system-wide administration. The high-rise residence halls were strengthened with external braces, and improvements were made in key classroom buildings and libraries.

Although campus planners have long been aware of the implications of a location astride the Hayward fault, the damage to relatively modern buildings in the 1989 Loma Prieta, the 1994 Northridge, and the 1995 Kobe earthquakes changed the approach for evaluating the safety of existing buildings. The earthquake losses in the 1990s prompted the campus to undertake another review of the structural conditions of all UC Berkeley buildings in 1996. The work was done by three leading structural engineering firms in the Bay Area: Degenkolb, Forell/Elsesser, and Rutherford and Chekene. Working together, the firms developed a systematic and consistent methodology for reviewing every building. The individual building reports were compiled into a 1997 document titled "The Preliminary Seismic Evaluation" (University of California, 1997a). The engineers used ground motion estimates developed in 1993 for the renovation of Hearst Memorial Mining Building to evaluate the structural performance of campus buildings in three earthquake scenarios. These scenarios, called the “Occasional, Rare, and Very Rare” correspond to earthquake ground motion probabilities, but can be more simply described respectively as a magnitude (M) 6+, a M 7.0, and a M 7.25 earthquake on the Hayward fault. For each scenario, the engineers rated the likely performance of each building according to the ten-point scale developed in “Vision 2000” (Hamberger, Court, and Soulages, 1995), an early performance-engineering document developed by the Structural Engineers Association of California. Table 1 briefly describes the ten performance states and compares them to post-earthquake damage tags developed by the Applied Technology Council, and the UC rating system which uses four categories “Good, Fair, Poor, and Very Poor.”

Based on the 1997 building review, almost one third of the space on campus was rated poor or very poor—subject to potential collapse in earthquakes. The information dramatically changed how campus administrators thought about seismic improvements for campus buildings. It was clear that the Berkeley campus was particularly vulnerable and that a more aggressive program was needed.

The Chancellor created the Seismic Action Plan for Facilities Enhancement and Renewal (SAFER) policy (University of California, 1997b) with an estimate of investing $20 million per year over twenty years. The University of California, Berkeley SAFER program combined funding available from bond measures for higher education with one-time funding from the Federal Emergency Management Agency (FEMA), and redirected campus budget monies to undertake what may be the largest program of seismic improvement of existing buildings in the world (see Table 2).

While the seismic investment was somewhat controversial because the program implied delayed investment in other programs and academic areas, the investment was justified by the compelling need to protect the safety of students, faculty, and staff.

The SAFER program was developed by Capital Projects staff with the assistance of then Vice-Provost Nick Jewell, and adopted as policy by Chancellor Berdahl. It is a remarkable policy document that clearly describes the seismic rating of each campus building and lays out a strategy for seismic repairs over a twenty-year period. In addition, the document proposes a ten-point administrative plan for disaster preparedness and long-range risk-management planning. The SAFER program outlines a building retrofit program; it provides public information to campus users; and it provides an outline for undertaking detailed emergency-preparedness planning.

Table 1. Comparison of Building Performance Rating Systems

U. C. BERKELEY RATING			SEAOC VISION 2000 RATING			ATC-20
Designation	Structural Damage	Hazard to Life	Numerical Rating	Performance Expectation	Anticipated Damage	
Good	Some Damage	Not Significant	10	Fully Operational	Negligible	
			9			
			8	Operational	Light	GREEN
			7			
			6	Life Safe	Moderate	
			5			
Fair	Damage	Low	4	Near Collpase	Severe	YELLOW
Poor	Significant Damage	Appreciable	3			
			2	Partial Collapse	Complete	
Very Poor	Extensive Damage	High	2	Partial Collapse-Assembly Areas		RED
			1	Total Collapse		

Table 2. Seismic Rehabilitation Timeline at UC Berkeley

Time Frame and Buildings	*Total Area Affected*
Pre-1997: Libraries, Residence Halls, Administration Buildings and Wheeler Hall	1,257,084 s.f.
In Construction 1997: Libraries, Residence Halls, Hearst Mining, McCone Hall	1,316,682 s.f
SAFER Projects Completed 2003: Art Museum, Barker, Barrows, Hildebrand, Latimer, Silver, Wurster Hall	971,669 s.f..
Phase 2 SAFER completed 2006: Central Dining, Stanley Replacement, LeConte, Hertz, and others.	95,700 s.f.
Phase 2 SAFER in design	367,574 s.f.
Phase 2 SAFER in planning stage	1,332,485 s.f.
Phase 3 SAFER planned	735,813 s.f.
TOTAL SEISMIC CORRECTIONS	6,077,007 s.f.

Initially, the sequence of buildings selected for structural retrofits was based on the hazard level and the number of occupants in order to address those buildings that posed the greatest life-safety threat. The buildings were designed to meet code-specified life-safety criteria, but additional performance engineering criteria were evaluated on a building by building basis by Capital Projects, the design engineer of record, and the campus Seismic Review Committee.

At the same time that the SAFER program was being formulated, Chancellor Berdahl met with FEMA Director James Lee Witt. They discussed the importance of understanding how potential earthquake losses would affect the university and its surrounding community, and how mitigation programs could lessen losses and economic impact. They asked Professor Mary Comerio to undertake a study of losses and economic impacts on the Berkeley campus that could serve as a model for other universities to assess their vulnerability to disasters and to develop risk-management strategies. That research project became the foundation for FEMA's Disaster-Resistant University (DRU) initiative, which provided risk-management funding to universities across the United States.

The Disaster Resistant University Initiative

The DRU initiative began with detailed loss and economic impact assessments for the three earthquake scenarios used in the Preliminary Seismic Evaluation. The work was directed by Professor Comerio heading a large team of faculty, students, and professional consultants. Geomatrix Engineers prepared a microzonation map of soil conditions and infrastructure locations for the campus. (A separate study of campus infrastructure had been completed and was available to the research team.) The same three structural engineering firms (Degenkolb, Forell/Elsesser, and Rutherford and Chekene, who undertook the 1997 evaluation) worked on an expanded structural and nonstructural building evaluation. Professor Vitelmo Bertero participated in the review and discussions. Professor Comerio and her students developed the loss estimates, Lynn Sedway and Associates and Professor George Goldman developed the regional economic impact, and

Professor John Quigley evaluated the economic impacts to research and academic continuity. The findings are detailed in a report titled, *The Economic Benefits of a Disaster Resistant University*, published in 2000 (Comerio, 2000).

In general, the campus loss study addressed the economic impact of potential losses under various earthquake scenarios. Loss estimates are not precise, as they include a range of probabilities for ground motion, building damage, and building replacement scenarios. The study posed a conservative range of dollar losses from approximately $6 million in an Occasional scenario to $2.4 billion in a Very Rare scenario. In addition to the cost of repairs, the study considered the time needed to make the campus habitable and operational. Even in a moderate earthquake, the study estimated that 19 percent of laboratory space could require more than twenty months for repair. In a magnitude 7.0 earthquake on the Hayward fault, the estimates ranged from 30 percent to 50 percent of all spaces needing more than twenty months for repair. Although the downtime estimates would clearly be reduced by the aggressive seismic strengthening program on the campus, the potential closure of laboratory and teaching space, and the possibility that the campus could be closed for one or more semesters, was a serious issue for the university.

The DRU study further suggested that closure of a university such as UC Berkeley, located in a large urban region, did not have a major impact on the regional economy. In an urban earthquake, the regional impacts would be distributed across the economy. However, for a major research institution, the true economic loss from earthquakes would stem from (1) the reduction of research output and (2) the loss of highly trained graduates who remain to work in the region. At the time of the study 75 percent of all funded research at UC Berkeley was conducted in just seventeen central campus buildings, and 50 percent of all funded-research took place in just five of those buildings. Unfortunately, three of the five were collapse hazards, but these buildings were not on the initial high-priority list because they were smaller buildings with fewer occupants. While life safety remained the top priority in the SAFER plan, it became clear that the ranking system used to select buildings for repairs needed to include additional criteria, such as research and teaching continuity.

The second key economic impact—the loss of graduates who contribute to the economy—is more subtle. Professor Quigley found that major universities perform what economists call a "sorting function." Students come to U. C. Berkeley for professional graduate programs, and many stay to work in the region or the state. It is common that about 20 percent of those who come from outside the state will stay after graduation. Thus, major firms find it advantageous to locate near major research institutions. If the university were forced to close, those students might go elsewhere and would not be available to work (and pay taxes) in the region or perhaps in California.

The economic findings of the study suggested that limiting downtime, avoiding the possibility of closure, and protecting the research investment were important goals in addition to protecting life safety. This led to a risk-management strategy aimed at the preservation of research and the stature of the university. The initial SAFER plan was expanded to include keeping the campus operational after an earthquake by limiting building downtime and limiting losses to valuable contents in laboratories and libraries. In addition, these findings prompted the campus to develop business resumption plans for teaching, research, business administration, facilities, and utilities. Some critical services, such as the campus computing center, were relocated as part of the larger risk-management plan, and additional investments were made in upgrading campus infrastructure.

Protection of Nonstructural Elements and Contents

Many building retrofit plans were designed with performance enhancements[1] to limit damage and maintain campus operations. At the same time, the impact of nonstructural retrofits on

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[1]The concept of "performance-based engineering design" suggests a dialog between engineer and client on what to expect from different design solutions. Using a performance-based model, engineers and architects quantify the technical needs and costs associated with expected outcomes, enumerating probable losses in terms of casualties, damage, and downtime. The client then makes a conscious choice among building systems, balancing front-end costs with long-term performance.

continuity was studied further. While most contemporary building codes contain provisions aimed at controlling damage to nonstructural (as well as structural) building systems (e.g., mechanical, electrical, plumbing), there are no similar requirements for a building's contents. In certain building types, such as museums, high-technology fabrication facilities, and research laboratories, the contents may be far more valuable than the building, and in some circumstances, may represent a potential hazard to the occupants and the general public. Seventy-two percent of the approximately $500 million in research funded each year is concentrated in science and engineering. The value of the laboratory contents is estimated at more than 20 percent of the total insured assets.

Equally important is the inestimable value of the research itself. Refrigerators and freezers contain irreplaceable specimens. Computer hard drives store data for research in progress. Laboratories represent both a concentration of research (as measured by annual funding) and a concentration of valuable equipment and ideas. In a study of laboratories on the campus, Comerio and Stallmeyer (2001) estimated that the average laboratory contents were valued at $200 to $300 per square foot. By comparison, in a typical office space the value of the contents is usually $25 per square foot.

Additional research funded by the Federal Emergency Management Agency (FEMA) and the Pacific Earthquake Engineering Research (PEER) Center focused on limiting downtime in modern laboratory buildings by protecting contents. The research involved detailed surveys of laboratory contents (Comerio, 2003), modeling of structural performance and shake table testing of key equipment to inform the loss models (Comerio ed., 2005), and development of design standards for contents anchoring (Holmes and Comerio, 2003). The process also included an evaluation of the impact of equipment vulnerabilities on downtime. The outcomes informed the development of nonstructural retrofit strategies and research recovery planning, and provided an analytic base data set for future loss modeling efforts.

The project involved a team of researchers from several universities conducting a case study, known in PEER as a "testbed." The study provided an opportunity to apply the PEER performance-based engineering methodology and to use the results to assist UC Berkeley in developing a strategy for protection of laboratory contents.

The PEER Laboratory Building Testbed

The case study building is located in the southwest quadrant of the campus, within 2 km of the Hayward fault. Completed in 1988, the building houses high-technology research laboratories. The building contents are typical for wet laboratories: lab benches with storage shelving above, and very densely packed equipment. In total, there are about 10,500 items in the building, of which 44 percent is furniture and 56 percent equipment. Shelves and work benches dominate the equipment category, while computers, heavy equipment such as refrigerators, freezers, and centrifuges, and bench-top items such as microscopes dominate the equipment group.

After analyzing the contents for life-safety concerns, the project team looked at the value of each item and its importance to the research. Only a small percentage of the equipment in the building was extremely specialized and valuable. Computers, refrigerators, and freezers dominated the “Important to Research” category because they contained data on research in progress or customized genetic materials. Thus, the loss of the contents of a refrigerator or freezer, or the loss of a hard drive, could effectively curtail research.

The building structure was analyzed using the PEER OpenSees structural analysis methodology. Shaking table tests of critical heavy floor-mounted equipment and bench-top configurations and equipment suggested that seismic excitation would result in sliding-dominated responses. The test results demonstrated average displacements of four inches for bench-top equipment (for a peak horizontal floor acceleration below 0.8g) and a peak sliding distance of almost 24 inches for heavy equipment. While the results from such tests do not provide a full understanding of equipment behavior, they do allow for preliminary estimates of losses.

The cost to anchor all the equipment in the testbed building was estimated at $20 per assignable (net) square foot. However, the costs for anchorage of high-priority items (i.e., those that posed a life-safety threat or deemed critical to research—about 40 percent of the building contents) would range from $2.50 to $13 per assignable square foot (Comerio, 2003), a reasonable cost for ensuring operations.

Using Research to Inform Design and Retrofit Decisions

The university allowed researchers to use actual building conditions and data for research with the understanding that the research would be used to inform the SAFER program decisions. In general, limiting downtime—the time buildings could be closed as a result of structural and nonstructural and contents damage, together with the time needed to mobilize financing, design, and construction work for repairs—is critical to maintaining university functions such as teaching and research. Numerous business resumption planning studies within UC Berkeley suggest that operations would cease if more than 25 percent of any functional space was closed for an extended period. Obviously, the dense urban setting precludes the use of extensive temporary facilities, so the university focused on the performance of existing facilities.

Overall, the planning performance goal was to limit a campus closure to thirty days or less so that a semester would never be cancelled due to earthquake damage. For each major function, classrooms, laboratories, libraries, and offices, space was analyzed in terms of its structural and nonstructural performance, and retrofit priorities were adjusted to reflect the overall risk. Laboratories were particularly vulnerable. Three of the five key laboratory buildings were collapse hazards, and a decision was made to replace these buildings with new structures rather than risk post-earthquake damage that could limit operations. Similarly, critical computing services were moved to a new facility. New food service buildings were also designed to be operational after an earthquake.

The potential for contents losses in other laboratory buildings led to a renewed Q-Brace program of seismic improvements for lab contents. Technical guidance was developed by PEER researchers in the form of an implementation manual (Holmes and Comerio, 2003) and training for campus construction staff.

Overall, the University of California, Berkeley, planning and construction staff, the consulting engineers and architects working on campus projects, the Seismic Review Committee, and PEER researchers have collaborated to introduce the concepts of performance-based design and risk management into the development planning for the university. The traditional engineering methods of identifying seismic hazards by building construction, and the risk-management approach to identifying critical operations combined to create a new mitigation methodology. The University of California, Berkeley, serves as a model for other institutions in the development of strategic risk management, and performance-based engineering practice.

References

California Seismic Safety Commission (CSSC). 2001. *An Evaluation and Assessment of the CSSC's Seismic Retrofit Practices Improvement Program, Proposition 122*. CSSC Report 2001-02, California Seismic Safety Commission, State of California, Sacramento.

Comerio, M. C. 2000. *The Economic Benefits of a Disaster Resistant University*. IURD WP #2000-02, University of California, Berkeley. Available at: http://www-iurd.ced.berkeley.edu/pub/abstract_WP200002.htm

Comerio, M. C. 2003. *Seismic Protection of Laboratory Contents: The U. C. Berkeley Science Building Case Study*. IURD WP #2003-02, University of California, Berkeley. Available at: http://www-iurd.ced.berkeley.edu/pub/abstract_WP200302.htm

Comerio, M. C. ed. 2005. *PEER Testbed Study on a Laboratory Building: Exercising Seismic Performance Assessment*. Pacific Earthquake Engineering Research Center, PEER Report 2005/12, University of California, Berkeley.

Comerio, M. C. and Stallmeyer, J. C. 2001. *Nonstructural Loss Estimation: The UC Berkeley Case Study*. Peer Report # 2002-01, Pacific Earthquake Engineering Research Center, University of California, Berkeley.

FEMA, 2003. *The Disaster Resistant University Guide*. Federal Emergency Management Agency, Department of Homeland Security, Washington, D.C. Available at: http://www.fema.gov/fima/dru.shtm

Hamburger, R. E., Court, A. B., Soulages, J. R. 1995. "Vision 2000: A Framework for Performance Based Engineering of Buildings," Proceedings of SEAOC Annual Convention. Indian Wells, California.

Holmes, W. T. and Comerio, M. C. 2003. *Implementation Manual for the Seismic Protection of Laboratory Equipment: Format and Case Study Examples*. PEER Report #2003-12, Pacific Earthquake Engineering Research Center, University of California, Berkeley.

University of California, Berkeley. 1997a. *Preliminary Seismic Evaluation*. Planning, Design and Construction, University of California, Berkeley.

University of California, Berkeley. 1997b. *Seismic Action Plan for Facilities Enhancement and Renewal (SAFER) Program*, University of California, Berkeley.

University of California, Office of the Vice-Provost, 2000. *Strategic Plan for Loss Reduction and Risk Management, University of California, Berkeley*. Available at: http://www-iurd.ced.berkeley.edu/pub/abstract_WP200003.htm


UC Berkeley–Seismic Upgrade Program
Hayward Fault
N
E
S
W
UCB - Facilities Services
Physical and Environmental Planning
01-26-2006
Completed Projects
Remaining Projects
Under Construction or in Design Phases
Concept / Planning Phases

Part One
East Campus

Hearst Memorial Mining Building

Stanley Hall Replacement

Latimer Hall

Hildebrand Hall

Jean Gray Hargrove Music Library

Wurster Hall

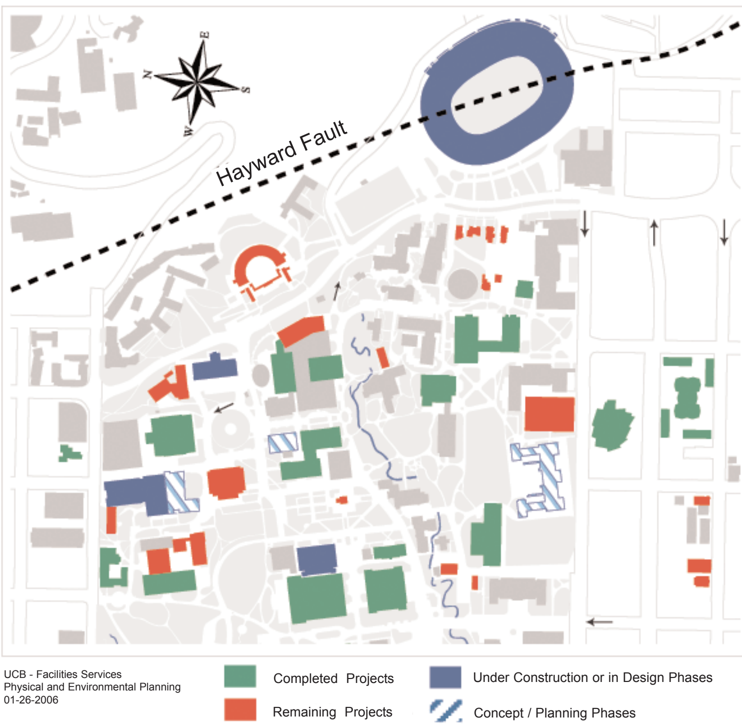
Archaeological Research Facility

New Residence Halls, Units 1 and 2

Crossroads Dining Facility

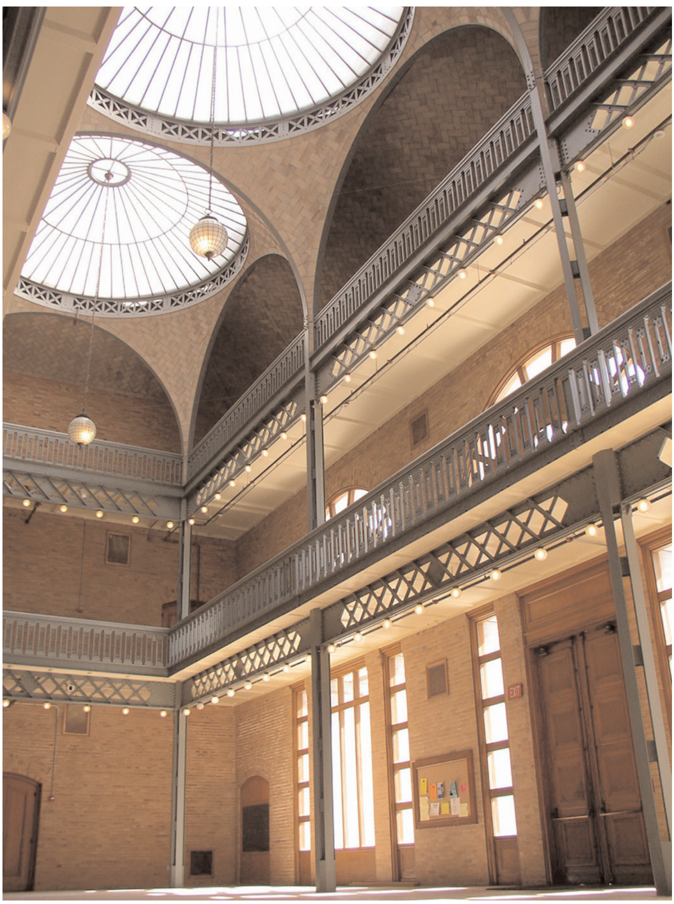
California Memorial Stadium

UC Berkeley–Seismic Upgrade Program



Hearst Memorial Mining Building

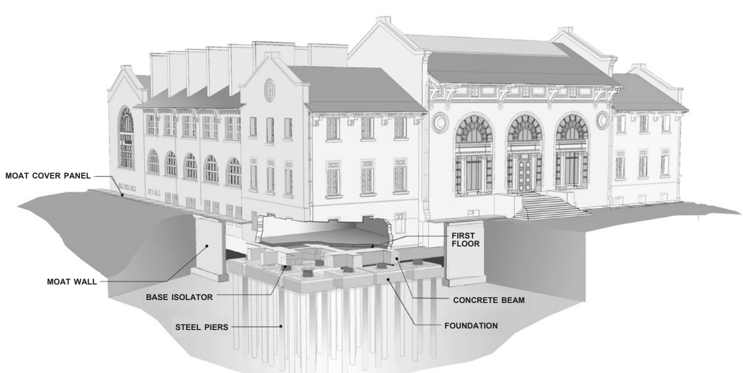
ARCHITECT:	JOHN GALEN HOWARD
DATE:	1907
SIZE:	130,295 SQ. FT.
RETROFIT ARCHITECT:	NBBJ
RETROFIT ENGINEER:	RUTHERFORD AND CHEKENE
DATE COMPLETED:	2002

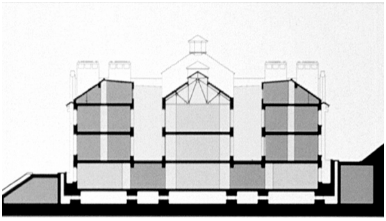


The Hearst Memorial Mining Building, designed by John Galen Howard, was completed in 1907. Phoebe Apperson Hearst, widow of Senator George R. Hearst, provided the funding for the building as a memorial to her late husband, who made his fortune in mining. The building is a four-story unreinforced masonry building with exterior cladding of granite masonry. The structural system consists of brick bearing walls with a very thin steel skeleton that was found to be inadequate to support the high gravity loads. An unreinforced concrete and brick foundation supported the steel-frame columns, the unreinforced brick masonry walls, and the concrete floors. The roof is surfaced with tapered clay tiles and copper sheet metal.

Hearst Memorial Mining Building (HMMB) was designed to be massive. Possibly its massive quality and the presence of steel in the structure were, at the time, considered sufficient to withstand the effects of earthquakes. Modifications were made in 1947 when the central gallery was infilled with reinforced concrete floors, providing three additional levels of assignable space. In 1949 and 1959 the open galleries above the laboratory space in the northern end of the building were filled in with reinforced concrete floors on steel framing to provide yet more additional space. Only the building's front, with its sky-lit

PREVIOUS PAGE:
Hearst Memorial Mining Building after retrofit.
BELOW:
Rendering showing base-isolation and foundation system.





LEFT:
Section of Hearst Mining Memorial Building.
BELOW:
Installation of base isolators.

lobby, remained as originally designed. Although only minor damage was reported in the Hearst Memorial Mining Building after the 1989 Loma Prieta earthquake, this temblor underscored the need to retrofit all unreinforced masonry buildings.

In a 1990 study conducted by the engineering firm of Rutherford and Chekene and the architectural firm of Esherick Homsey Dodge and Davis (EHDD), several seismic deficiencies were found in HMMB, based on the University Seismic Safety Policy of 1978. The masonry brick walls were overstressed in shear; floor slabs were not tied to the masonry brick walls; the front facade did not adequately resist lateral loads; and the chimneys, terra cotta tile ceilings, and stone ornamentation were considered falling hazards. Two strengthening schemes were considered.

In the first scheme, the engineers suggested adding steel-braced frames to the building and tying the slabs together to enable the transfer of lateral loads. This retrofit scheme was considered intrusive and it would detract from the design of HMMB—a

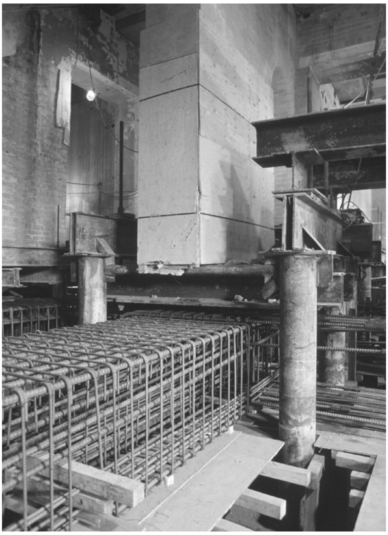
RIGHT:
Detail of installation of base isolators

building with considerable historical significance. The second retrofit option was more compatible with the building's original design and included adding concrete shear walls to the interior face of existing walls and tying the slabs to enable the transfer of lateral loads. In 1992, recognizing the importance of HMMB to the university and surrounding community, the university considered using a relatively new technology, base isolation, to improve the seismic performance of HMMB. As a result, a more advanced study was performed in 1993 by Rutherford and Chekene with exhaustive analysis, masonry testing, and shear tests.

The proposal to use base isolators as part of the retrofit scheme raised a number of structural design issues. First, because of HMMB's architectural importance and its location on a rocky site adjacent to the Hayward fault, it was necessary to accurately define the ground motions in order to effectively use base isolators. A second key issue was the "fault parallel" effect[1]. This effect is felt most significantly on sites very close to a fault rupture. How to design and use the relatively new technology of base isolators was a third issue. After a schematic design was completed in 1996, there was a special peer-review process in recognition of the complexity of the design.

The Hearst Memorial Mining Building's base-isolation system consists of 134 steel and rubber-laminated composite columns, called "base isolators," which can move 28 inches in any horizon-

[1] When a fault ruptures, two portions of the surface of the earth move in opposite directions while shock waves propagate perpendicular to the fault. The ground motion resulting from the first phenomenon is parallel to the direction of the fault.



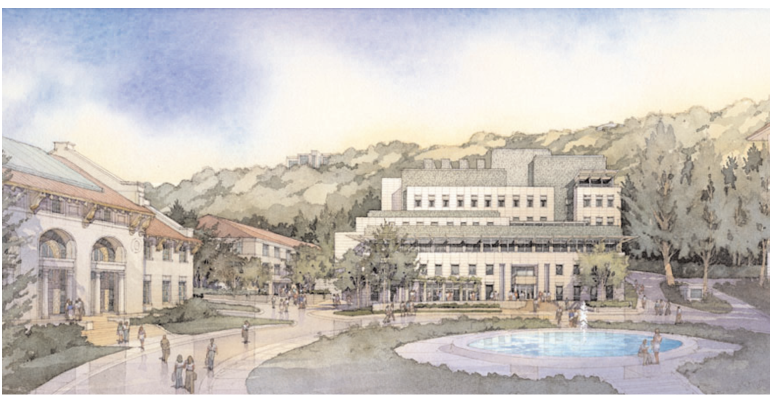
LEFT:
Detail of installation of base isolators.

tal direction, allowing the building to safely ride out earthquakes. The technology was pioneered by UC Berkeley Engineering faculty more than twenty years previously. Base isolators are made with elastomeric bearings that decouple the building from the horizontal components of the ground motion by interposing structural elements with low horizontal stiffness between the structure and the foundation. This layer gives the structure a fundamental period that is much higher than that of a fixed-base foundation system. The type of isolators used for HMMB are called "multilayered laminated rubber bearings," with steel-reinforcing layers as the vertical load-carrying component of the system. Because of the reinforcing steel plates, these bearings are very stiff in the vertical direction, but are flexible in the horizontal direction. Easy to manufacture, these bearings have no moving parts and are very resistant to environmental degradation.

The Hearst Memorial Mining Building's seismic retrofit not only strengthened the building, but also allowed the opportunity for significant upgrades. Additional space was created underground to house mechanical equipment, and two new three-story buildings were added at the north face. The scheme included the preservation of the building facades; restoration of the south wing, including the Memorial Gallery, offices and classrooms; retention of the appearance of the historic facades along each side of the building; and the stabilization of the chimneys. The retrofit made use of a new engineering concept called performance-based design, which consists of providing structural performance that is superior to what is required by the codes and better adapted to the building and its function.

Stanley Hall Replacement

ARCHITECT:	MICHAEL GOODMAN
DATE:	1952
SIZE:	65,059 SQ. FT.
REPLACEMENT ARCHITECT:	ZIMMER GUNSUL FRASCA PARTNERSHIP
REPLACEMENT ENGINEER:	RUTHERFORD AND CHEKENE
DATE COMPLETED:	IN PROGRESS
NEW SIZE:	240,000 SQ. FT.



ABOVE:
Watercolor of new Stanley Hall.
Photo courtesy of ZGF Architects.

Latimer Hall

ARCHITECT:	ANSHEN AND ALLEN
ENGINEER:	DEGENKOLB ENGINEERS
DATE:	1966
SIZE:	183,615 SQ. FT.
RETROFIT ARCHITECT:	ANSHEN AND ALLEN
RETROFIT ENGINEER:	FORELL/ELSESSER ENGINEERS
DATE COMPLETED:	2001

ABOVE:
Latimer Hall after retrofit.

LEFT:
Latimer Hall before retrofit.

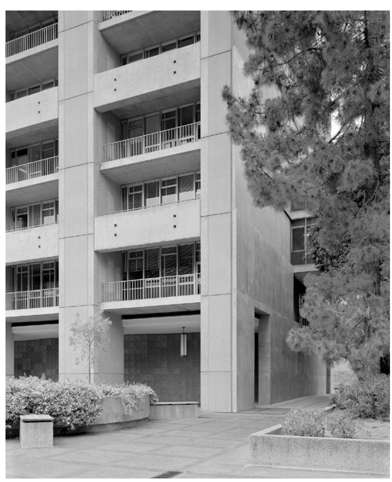
From 1960 to 1966 the University of California at Berkeley constructed two new buildings to house the College of Chemistry: Latimer Hall and Hildebrand Hall. The buildings had the same architect but two prominent engineers with diverging attitudes toward seismic-resistant design; Henry Degenkolb (1913–89), world-renowned expert in earthquake engineering, designed Latimer's structural system, while T.Y. Lin (1912–2003), internationally recognized for his edgy and bold designs using prestressed concrete, designed the Hildebrand Hall structure. Both buildings were found to be seismically unfit in a 1997 review, and in 2001 both received extensive retrofits as part of the university's SAFER program. That both buildings needed retrofits is a testament to the past four decades' dramatic growth in the body of knowledge regarding earthquake engineering.

Henry Degenkolb graduated with a degree in civil engineering from UC Berkeley in 1936. Although Degenkolb had been practicing for over two decades by 1960 when Latimer Hall was designed, the industry's knowledge of building performance in earthquakes was still nascent. A string of earthquakes (Alaska 1964, Caracas 1967, and San Fernando 1971) spurred a period of intensive investigation of earthquakes and a revision of building codes. When Degenkolb designed Latimer Hall, the code was a very thin document compared to today, but he recognized the threat of earthquakes and, like many engineers in California, designed beyond the code.

In addition to two basement stories, the 184,000 square foot building has nine stories above ground in a rectangular tower that accommodates 831 laboratory stations and 213 fume hoods. The building's program required a floor plan that was unimpeded by walls and columns to allow for a flexible laboratory layout. The volume and complexity of the building program and needed services substantially influenced the design of the building. To develop an architectural solution that successfully addressed all of the project's challenges, the architectural firm of Anshen and Allen worked closely with Degenkolb Engineers.

To provide strength to the main structure of the building, the project team used exterior concrete box columns for the retrofit. These large, hollow columns visibly line the exterior of the north and south sides of the building. They are like large square donuts, 7 feet 3 inches wide, spaced 27 feet apart, and constructed of 14-inch-thick walls of poured concrete heavily reinforced with steel rebar. These columns provide the major structural support for the building and house the large ducts that drain the laboratory fume hoods, leaving each floor with an open plan. Openings in the columns at each floor made access for maintenance or modification relatively easy. The columns also provide a highly visible architectural expression of the building's structural and mechanical systems, announcing, as a series of exterior fume hoods would, the activities taking place within.

These concrete box columns along with the floor diaphragms connecting them provided the lateral force resistance in the longitudinal direction. Short shear walls at the stair and elevator cores also provided longitudinal shear strength. Lateral force resistance in a transverse direction was supplied by large concrete shear walls capping the east and west ends of the building, aided by the walls around the elevator core. Gravity loads were shared by the perimeter box columns, the elevator and stair cores, and twelve steel columns in the interior of the building.



RIGHT:
Latimer Hall retrofit completed.

ABOVE:
Elevation showing placement of box columns.

In 1996–97 UC Berkeley enlisted Degenkolb Engineers to do a preliminary seismic evaluation of Latimer Hall. This brief review of the building determined that in the case of a Rare earthquake (one with a 10 percent chance of occurring within fifty years) the building would perform with a Poor, or near-collapse, rating. This expected performance was due mainly to deficiencies in the longitudinal lateral force-resisting system. The box columns and the floor slabs spanning the distance between them were designed to act as moment frames that resisted applied shear force. However, the floor slabs were not continuous through the box columns, and their attachment to the columns was insufficient for the system to behave like a true frame in the event of a strong lateral load. The other longitudinal walls were too slender to add significant lateral support. Other deficiencies were also noted in the transverse direction, namely that the stress in the transverse shear walls would exceed capacity, and that openings at the first level of these walls weakened them.

The Poor rating of the building, its size, and number of occupants made Latimer Hall a high priority for a seismic retrofit. Anshen and Allen once again acted as architects and Forell/Elsesser Engineers were hired as the structural engineers. The retrofit began in 2000.

LEFT:
Detail of box columns.

The architects and engineers worked together to find a retrofit solution that would not block light into the lab spaces. Rather than introducing a new structural system into the building, the selected strategy strengthened the building's existing system. This scheme essentially consisted of adding more reinforced concrete to the existing columns, beams, and walls at the building's exterior. At the longitudinal walls, a 19-inch-thick concrete column was doweled to the outside face of each box column. The connection between the box columns was strengthened by the addition of 5½-foot-deep by 19-inch-thick concrete beams at odd-numbered floors, as they were not needed at every floor. Footings under each column were also augmented. Increased strength in the transverse direction was achieved by thickening and reconfiguring the shear walls at the east and west facades by improving their connections to the ground.

Because the retrofit scheme only intervened at the exterior of the building, Latimer Hall remained fully operational throughout the retrofit. However, coordinating the shuffling of the building's occupants during construction proved to be one of the most challenging aspects of the project. The noise of jackhammers chipping away at the existing concrete to tie in the new pieces became an expected part of a chemistry student's day. Today, an observant eye can easily spot the difference between the original concrete and the new concrete added in the retrofit. The building continues to express its structural and mechanical systems on its exterior, now with a new layer that serves as a testament to the quickly changing field of earthquake engineering.

Hildebrand Hall

ARCHITECT:	ANSHEN AND ALLEN
ENGINEER:	T. Y. LIN
DATE:	1966
SIZE:	136,996 SQ. FT.
RETROFIT ARCHITECT:	ANSHEN AND ALLEN
RETROFIT ENGINEER:	FORELL/ELSESSER ENGINEERS
DATE COMPLETED:	2001

ABOVE:
Hildebrand Hall after retrofit.

ABOVE:
Hildebrand Hall before retrofit.

In 1963, the university began work on Hildebrand Hall. The consulting structural engineer for the project, T. Y. Lin, was known internationally as the "father of pre-stressed concrete," a technology that fundamentally broadened the possibilities of architecture, engineering, and construction. Although pre-stressing technology[1] was first invented in the 1940s, T. Y. Lin was the first to make it practical, economical, and popular. He enthusiastically recognized its enormous potential, not only for saving money but also for bringing a new freedom to architecture.

Located on the east side of campus, Hildebrand Hall lies adjacent to the south side of Latimer Hall. A system of underground passageways connects the two buildings and other adjacent labs. Completed in 1966 by the architectural firm of Anshen and Allen, Hildebrand Hall consists of two partially underground floors and a three-story tower that rises from the plaza level. The first level of the tower houses the Chemistry Library, while the two lower floors and the two upper floors contain labs, workshops and storage spaces. These top two floors cantilever over the glazed library level. The building's site slopes dramatically to the south, exaggerating the effect of the cantilever. Designed to achieve architectural harmony with the adjacent buildings, the materials palette included concrete, glass and terracotta.

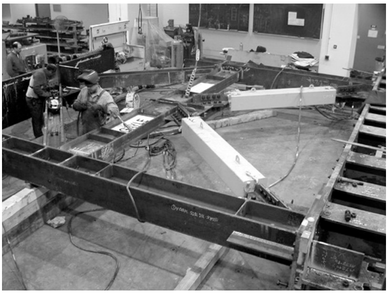
[1]Reinforced concrete derives its strength from embedding steel, which is extremely strong in tension, in concrete, which is strong in compression but weak in tension. In a conventional reinforced concrete slab or beam the normal bending forces put the bottom portion into tension, causing cracking at the bottom part of the beam. In a prestressed slab or beam, an initial tensile force is applied to the reinforcing steel prior to the pour. After the concrete cures, the steel tendons are released, causing the entire slab to go into compression thus eliminating the tension stress at the bottom portion of the concrete and increasing the capacity of the slab. Prestressed slabs and beams can therefore be much thinner than conventional reinforced concrete, decreasing the weight and cost of each element and allowing for more innovative designs. The savings can approach fifty percent in concrete weight and twenty percent in steel weight.

ABOVE:
Interior view of unbonded braces.

The structural system of Hildebrand Hall was minimal and concealed and lacked shear-resisting elements to a degree almost shocking by today's standards. The concrete stair and elevator provided the only lateral force resistance in the building. The cores shared the gravity loads with eight interior columns and a series of box and fin columns at the edge of the first floor. Acting like a set of shoulders supporting the cantilevered second and third floors, the roof plane was specially engineered with increased thickness at the center to resist the bending forces caused by the weight of the cantilever.

In 1997 Forell/Elsesser, Rutherford and Chekene, and Degenkolb Engineers completed a joint seismic analysis of Hildebrand Hall. The analysis predicted that the interior columns would punch through the floor slabs, causing widespread structural collapse at all three floors of the tower. The precast panels' connections to the second and third floor slabs were expected to break due to lateral motion, and the library mezzanine was expected to collapse due to a lack of lateral resistance.

Anshen and Allen and Forell/Elsesser investigated numerous retrofit strategies for Hildebrand Hall and finally decided to use unbonded braces, which were a very new and promising addi-



LEFT:
Lab testing of unbonded braces.
BELOW:
View of unbonded braces.

tion to anti-seismic technology. Unbonded braces work in a simple and elegant manner. In a traditional steel cross-brace, lateral forces are resisted axially by each cross-member. An applied lateral force will stretch one cross-member in tension and shorten the other in compression. Unbonded braces are made of steel (which is strong in tension) and concrete (which is strong in compression), enabling the braces to exhibit nearly identical properties in both tension and compression. In addition to the braces, new concrete shear walls providing lateral support were added to the two lowest stories, and on the east, west, and south sides a portion of the shear walls extended up to the roof. The walls around the stair cores were strengthened and reinforcement was added to the column-to-slab connections, mitigating the threat of punching shear by the columns. The connections between the precast panel hangers and the roof and floor slabs were strengthened as was the mezzanine level of the library.

LEFT:
Detail of unbonded brace.

Although Hildebrand Hall's original structural design was quite deficient by today's standards, it did meet the requirements of the 1958 Uniform Building Code in use at the time it was completed. It was not until the San Fernando earthquake in 1971 that the importance of ductility in buildings was understood. Hildebrand Hall was nonductile, lacking many of the design elements and reinforcing details required by codes written after 1971. Lessons learned from recent earthquakes and advances in computer modeling of structural systems have enabled engineers to assess a building's movement during earthquakes, and design for better performance.

(New) Jean Gray Hargrove Music Library

ARCHITECT:	MACK SCOGIN MERRILL ELAM
ENGINEER:	OVE ARUP AND PARTNERS
DATE:	2004
SIZE:	28,775 SQ. FT.

Wurster Hall

ARCHITECT:	DE MARS, ESHERICK AND OLSEN
ENGINEER:	ISADORE THOMPSON
DATE:	1964
SIZE:	216,468 SQ. FT.
RETROFIT ARCHITECT:	EHDD ARCHITECTURE
RETROFIT ENGINEER:	RUTHERFORD AND CHEKENE
DATE COMPLETED:	2002

ABOVE:
View of west tube under construction.

Completed in 1964, Wurster Hall was designed by Joseph Esherick, Vernon DeMars, and Donald Olsen to house the College of Environmental Design (CED). William Wurster, the dean of the college, selected this team of faculty members to design the state-funded building. Built of reinforced concrete, the 140,000 square foot building was designed to accommodate the rough treatment associated with the training of architects and artists. Reinforced concrete offered not only the economic advantages but also the sculptural quality that the designers desired. The construction of the building included a combination of cast-in-place concrete with precast elements. The floors and roof were poured in place, while the exterior columns and sunshades were precast. Isadore Thompson, the structural engineer for the project, had also worked on the Berkeley Art Museum, another campus building that exemplifies an innovative use of structural concrete. The interior of Wurster Hall was left unfinished to expose the various building systems. All of the mechanical and electrical systems were suspended from the ceiling since imbedding them in the concrete slab would make maintenance impossible.

In the 1978 Degenkolb report, Wurster Hall received a Fair seismic rating. However, this evaluation was based on the building's construction type—a cast-in-place concrete structure with precast elements—and did not include an examination of the structural elements themselves. After the Loma Prieta earthquake in 1989, Professors Mary Comerio and Stephen Tobriner lobbied for a detailed seismic review to be undertaken. The campus office of Planning, Design and Construction hired Ephraim G. Hirsch to

ABOVE:
New interior steel columns in the tower.
BELOW:
Reinforcing bars in new drag struts.

complete an in-depth analysis of Wurster Hall in 1997. In his analysis, Hirsch found that the ten-story tower had little bracing in the east-west direction, and that the tower's existing shear walls were discontinuous, likely resulting in collapse of the tower during a major seismic event. Additionally, Wurster Hall's U-shaped plan with deep reentrant corners suggested the potential for high lateral stresses at the intersection of the north and south legs. Due to sectional asymmetry, the ten-story north tower would experience a different acceleration period compared with the four-story south end of the building. In order to strengthen the building, Hirsch proposed adding precast steel-braced frames inside the facade of the existing structure.

Initially, Wurster Hall was scheduled to be completed in a later phase of the campus SAFER program. However, in calculating the number of people that occupy each building, campus planners found that Wurster Hall had one of the highest overall occupancies on campus; as a result the Seismic Review Committee recommended Wurster Hall be given priority. At this same time the 1997 building code had

changed significantly based on lessons learned from recent earthquakes. The code revisions required a new analysis and design approach.

A building committee was convened in the fall of 1997 to review the retrofit process. The committee included members of the College of Environmental Design faculty and students, and university representatives from Planning, Design and Construction. The committee interviewed a number of potential teams to complete the retrofit project and selected the architectural firm of Esherick, Holmsey, Dodge and Davis (EHDD) with structural engineers Rutherford and Chekene. Another committee

ABOVE:
Rebar laid out for foundation.
RIGHT:
Construction of new shear wall.

was formed to work with these architectural and engineering firms to develop a creative, cost-effective, and functional solution. Members of the CED wanted the retrofit to solve the poor seismic condition and to enhance the existing structure as well.

Before designing retrofit schemes, Rutherford and Chekene performed a structural analysis to determine the forces and displacement that would be exerted on the building by a significant earthquake. In addition to the deficiencies found by Hirsch, the central wing was determined to be lacking support along the northern edge, threatening partial collapse in a major event. Furthermore, the interior and perimeter fin columns lacked sufficient lateral reinforcement to resist the large story drift that could occur in the ten-story tower.

Many retrofit schemes were then proposed by the design team. These schemes included closing off the central courtyard, adding perimeter interi-

ABOVE:
Library during construction.
RIGHT:
View of pier connection jacket.

LEFT:
View of hand-dug pier below lobby.

or steel bracing, and constructing external buttresses. The project committee selected a design that involved adding two tube-like structures on the east and west sides of the tower. These tubes would brace the tower and provide lateral support. Unlike a number of the other proposals, the tube scheme proposal allowed for extra program space on all of the studio floors. The scheme also included adding new shear walls and foundations to help resist lateral forces, thereby minimizing potential displacement of the tower. Collector beams in the diaphragm were designed to tie the new tube shear walls together with the existing structure. New foundations supported by drilled piers 60 feet deep were added under the tubes. To strengthen the fin columns, a series of steel columns were added on the interior of the facade to transfer the vertical loads. Interior columns were fiber-wrapped to increase strength.

Several issues came up during construction that necessitated making changes to the selected scheme. Before pouring the foundations for the new tubes, holes for the new piers had to be drilled below the existing lobby and on the exterior of the east tower facade. Large drills were used for the exterior piers; however, height constraints under the lobby precluded the use of drilling equipment. Hand-digging these holes was the only option. Although the new piers were originally designed with a two-foot diameter, this dimension did not allow sufficient space to enable digging by hand. The piers were resized to a four-foot diameter, which increased their strength and allowed the engineers to reduce the number of piers in the lobby. While the exterior machine-drilled holes took only a day each, the hand-dug holes under the lobby took two months to complete.

As the retrofit scheme required large amounts of concrete, EHDD chose to use concrete made with fly ash, a by-product of coal-fired power plants. Fly ash can be substituted for a portion of the cement in a concrete mix, making it a more sustainable product. The standard percentage of fly ash used in concrete is 10–15 percent, but EHDD persuaded the college to use 40–50 percent fly ash in the new slab foundations. Although using a high volume of fly ash in concrete requires a longer curing period, it also increases the long-term strength and durability of the concrete and decreases permeability.

In addition to the seismic renovations, the retrofit project included the installation of new mechanical systems, electrical wiring, fire sprinklers, and upgrades to the telecommunication systems throughout the building. Since these systems in the original building were exposed and suspended from the ceiling, all the new duct work, conduits, lighting, and sprinkler pipes were installed in a similar fashion. Completed in 2003, this project provides a unique case study that highlights the many challenges of a retrofit project.

Archaeological Research Facility

ARCHITECT:	CHARLES PETER WEEKS
DATE:	1920
SIZE:	12,750 SQ. FT.
RETROFIT ARCHITECT:	PATRI-MERKER
RETROFIT ENGINEER:	FORELL/ELSESSER ENGINEERS
DATE COMPLETED:	2002

ABOVE:
Archaeological Research Facility, view of the east entrance.

New Residence Halls, Units 1 and 2

ARCHITECT:	EHDD ARCHITECTURE
ENGINEER:	RUTHERFORD AND CHEKENE
DATE:	2005
SIZE:	267,500 SQ. FT.

ABOVE:
View of new Slottman Residence Hall from the courtyard.

Crossroads Dining Facility

ARCHITECT:	CANNON DWORSKY
ENGINEER:	OVE ARUP AND PARTNERS
DATE:	2002
SIZE:	40,331 SQ. FT.

ABOVE:
View of main entrance to Crossroads Dining Facility. The new office building is behind Crossroads.

California Memorial Stadium

ARCHITECT:	JOHN GALEN HOWARD
ENGINEER:	GEORGE F. BUCKINGHAM and EDWARD E. CARPENTER
DATE:	1923
SIZE:	297,997 SQ. FT.
RETROFIT ARCHITECT:	HANSEN/MURAKAMI/ESHIMA (phases I, II, III)
	HNTB ARCHITECTURE (phase IV)
RETROFIT ENGINEER:	MESSINGER AND ASSOCIATES (phases I, II, III)
	FORELL/ELSESSER ENGINEERS (phase IV)
DATE COMPLETED:	1994 (phases I, II, III)
	IN PROGRESS (phase IV)

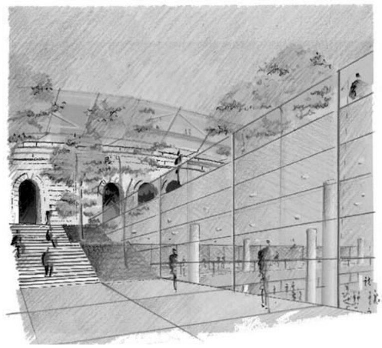
ABOVE:
Aerial view of California Memorial Stadium.

ABOVE:
Rendering by HNTB of proposed stadium renovations, 2005.

In October of 1921 the University of California initiated a state-wide campaign to construct a football stadium on campus as a memorial to the Californians who had lost their lives in World War I. Within a month, more than $1 million was pledged. Three remote sites and three university-owned sites were considered before the final unanimous vote by the Executive Committee of the Associated Students of the University of California (ASUC) located the stadium at the basin of Strawberry Canyon. This decision was met with much protest, and a community-based Campus Protective Association was formed to oppose the Strawberry Canyon location given the constraints of the topography, and concerns about limited transportation and accessibility, and the loss of the natural landscape.

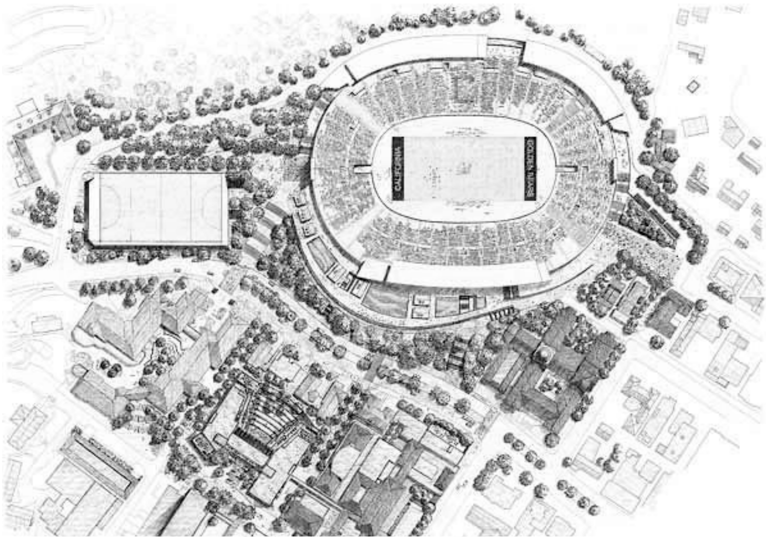
John Galen Howard, the official campus architect, was also opposed to the Strawberry Canyon site. In a letter to UC Berkeley President D. P. Barrows, on January 12, 1922, Howard declared that the approved site was extremely problematic; parking was a notable problem, the adjacent streets were narrow and few, and the exits were too small and scarce, to allow for proper handling of crowds. Howard had already designed an arched double-deck oval coliseum for a different site at Allston and Ellsworth streets, yet despite his persistence the site selection remained unchanged.

At the same time, Edward E. Carpenter, a partner in the engineering firm of Baker and Carpenter, lobbied for the Strawberry Canyon site, suggesting the potential cost benefits of using its natural grade to aid in structuring the stadium as an earthen bowl, whereby the ground would support the seating. Seeing the merit in both Howard's and Carpenter's proposals, engineer George F. Buckingham offered a combination of the two ideas, which was readily adopted by the regents in August 1922. A stadium design commission was appointed composed of Howard as the chairman, Buckingham, Carpenter, and the University Controller and Secretary of the Regents Robert Gordon Sproul. Plans were finalized in 1923 and, within the same year, the final design was partially cut into the hillside with a western facade towering 67 feet above the ground.



ABOVE:
HNTB rendering of proposed training and sports medicine facilities on the west side of Memorial Stadium.

The site proved difficult for several reasons. The Hayward fault runs along the major axis of the final design, and the drainage from the steeply sloping Strawberry Creek basin had to be conveyed under the playing field through a four-foot diameter 1,450-foot-long concrete culvert. Alluvium soil, the Strawberry Creek floodplain, and fill also complicated the foundation. To address these difficulties, the east side was composed of a reinforced concrete structure resting on slab-on-grade construction that followed the slope of the existing hillside with cuts ranging from rock to soft earth. The west side was supported partly on fill and partly by a suspended concrete frame resting on columns that extend far below the surface to a creek bed. Hundreds of square pillars, 20 x 24 feet supported the field, while a continuous concrete foundation wall followed the curving west facade. The west side was divided into three seismically isolated segments that are separated by expansion joints. Seating was fastened to a concrete slab, beam and girder system that was in turn supported on con-



ABOVE:
Integrated projects proposed for the southeast quadrant of campus include the renovation of California Memorial Stadium.

crete columns. The exterior walls were reinforced concrete with concrete walls running longitudinally, connecting the east and west sides.

To the delight of Berkeley fans, the stadium opened just in time for the Big Game of 1923. By 1947 the stadium was beginning to show the stresses placed upon it by weathering and varying foundation conditions. A report by Walter T. Steilberg, the consulting architect for the ASUC, indicated the need for structural repairs. Steilberg made numerous recommendations including the need for careful analysis in relation to the consequence of an earthquake.

A report prepared by Marvin Buchanan for the Campus Planning Study Group in June of 1980 described the need for renovations to the existing Intercollegiate Athletics facilities. The report described many aesthetic changes that should be made to the stadium, such as the addition of trees and new ticket booths as well as improved circulation patterns. Making a brief interlude into the potential for seismic considerations, the report stated "The

Stadium is also located in the Alquist-Priolo Study Zone. The Hayward fault passes through the Stadium. Clearly an extensive seismic study must precede any new construction within the Stadium and special care will have to be taken with all structural work, fire protection, exits and utility systems."

Many of the programmatic and aesthetic suggestions were implemented under the Cal Sports 80s project, an $8 million dollar renovation of athletic facilities at Berkeley. A plan was devised by Hansen/Murakami/Eshima (architects), Messinger and Associates (structural engineers), and Kaldveer & Associates (geotechnical engineer) for the renovation to California Memorial Stadium whereby improvements would be made in four phases. Phases I, II, and III were completed in 1994, but the final phase was delayed by the university requirement to upgrade the seismic strength of the stadium. The campus Seismic Review Committee (SRC), noting that maximum attendance would reach 70,000 people, expressed concern for life safety: "The west portion of the UC Berkeley Memorial Stadium is supported by a nonductile reinforced concrete structure designed in 1922 and…portions of the concrete structure have been subjected to fault creep since 1924 which has offset portions of the structure as much as 4–5 inches."

A new multi-year plan for refurbishing Memorial Stadium was put forward in November of 2005. The plan includes a privately funded athletic center along with an upgrade of existing facilities. The design team includes HNTB Architecture for the stadium, and Forell/Elsesser Engineers for the seismic improvements included in the master plan.

Part Two
Central Campus

Berkeley Art Museum

Hearst Field Annex / Pacific Film Archive

Barrows Hall

Jane K. Sather Tower

South Hall

LeConte Hall

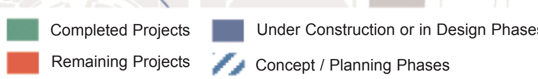
Doe Library

Moffitt Library

McCone Hall

UC Berkeley–Seismic Upgrade Program

UCB - Facilities Services
Physical and Environmental Planning
01-26-2006



Berkeley Art Museum

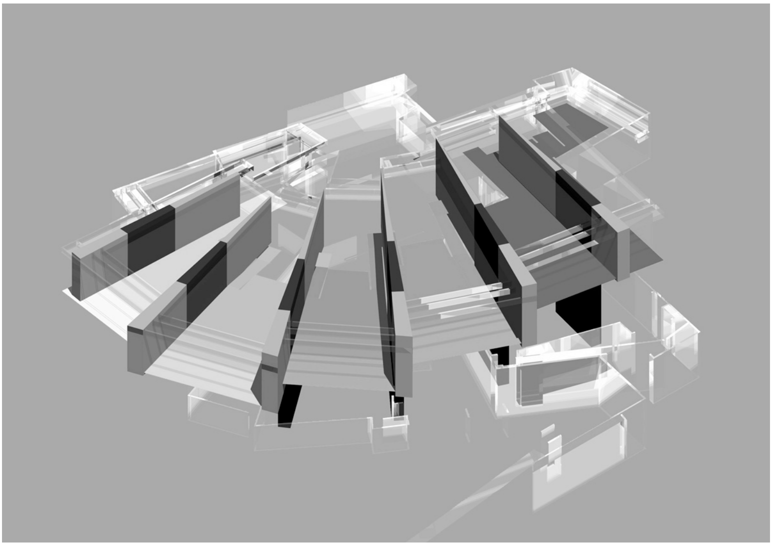
ARCHITECT:	MARIO CIAMPI
ENGINEER:	ISADORE THOMPSON
DATE:	1970
SIZE:	105,833 SQ. FT.
RETROFIT ARCHITECT:	C. DAVID ROBINSON ARCHITECTS
RETROFIT ENGINEER:	FORELL/ELSESSER ENGINEERS
DATE COMPLETED:	2001

ABOVE:
Berkeley Art Museum after retrofit with new steel columns.

In 1964 the University of California launched a competition to find an architect for a new University Art Museum. The German artist Hans Hofmann's donation of a number of paintings along with a generous monetary gift, combined with curator Peter Seltz's energetic efforts to secure a space for exhibiting modern art, initiated the plans for an art gallery. In 1965, out of 366 entries, Mario Ciampi's project won the competition. Isadore Thompson was later brought on as the project engineer.

Completed in 1970, Ciampi's bold and innovative reinforced concrete building consists of a three-story fan-shaped plan with a series of stepping galleries radiating from an entrance lobby. The western walls of the lower galleries are glazed, allowing visitors to view the western sculpture gardens. Multiple skylights provide light from above with the largest positioned directly over the entrance lobby. Six "tree walls," freestanding rectangular reinforced concrete walls with

ABOVE:
View of exterior before retrofit.
BELOW:
View of cantilevered galleries before retrofit.



ABOVE:
Isometric drawing showing fan-shaped galleries and shear wall system.

80-foot cantilevered beams allow for the opening up of the gallery spaces below and the ramps that direct patrons to move easily between levels. Structurally, the building can be described as a combination shear wall and cantilever system. The exposed cantilevers fan out and step down, supporting the roof and skylights above and creating exterior walls by connecting to intersecting beams.

Not until years after construction did engineers discover that some of the design employed to make the museum such an innovative building also made it extremely vulnerable to natural disaster. Its stepped configuration, cantilevered tree walls, expansive entrance skylight, and window walls on the lower story contribute significantly to the unique character of the space. However, these same elements compromise the structural integrity of the building with respect to seismic forces.

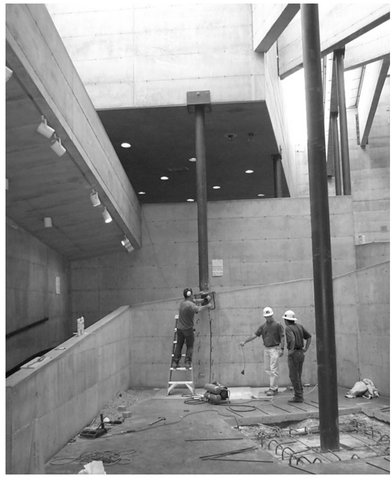
Like other campus buildings, the museum was built to code at the time of construction, but a 1997 seismic evaluation found the building to be inadequate. A preliminary seismic evaluation conducted by SOH & Associates initially downgraded the Museum from a rating of Fair to Poor. The main concern was the fundamental lack of redundancy in the connections within the building frame. SOH & Associates ultimately suggested that the expected building performance in the event of an earthquake would be Very Poor, citing the likelihood of falling hazards, cracking damage, and partial or extensive collapse.

In 1997, Forell/Elsesser Engineers were asked to perform another seismic evaluation of the Museum and to propose conceptual seismic upgrade schemes to inform the budget process. Forell/Elsesser concurred with SOH & Associates' rating of Very Poor. The primary problems they identified were lack of adequate seismic-resistant elements in the direction perpendicular to the tree walls; lack of continuous and reliable load path; lack of redundancy; lack of ductility; major vertical discontinuities and weaknesses; major diaphragm discontinuities; and falling hazards.

A week-long charrette with five design teams was held to formulate the seismic and spatial design issues. In 1999, the university embarked on a feasibility study to compare retrofit and expansion schemes, and to clarify the benefits of one plan of action over the others, considering both the museum's space needs and seismic deficiencies. The 1999 study determined that a retrofit and expansion scheme would have a similar price tag as a new construction scheme, but the museum community ultimately decided that constructing a new building would be the best option. Until funds were raised, the museum had to continue to operate, but the original building's considerable existing seismic deficiencies

LEFT:
Installation of exterior steel columns.

RIGHT:
Installation of interior steel columns.



called for an immediate plan of action. To this end a temporary and partial strategy was implemented to mitigate imminent dangers to the building and its occupants. Forell/Elsesser developed a low-cost solution that would address the building's most salient structural issues and therefore increase its capacity to resist seismic forces. The scheme consisted of additional supports both inside and out to augment resistance to seismic loading, and the use of trusses to tie the ceiling diaphragm together across the perimeter skylights.

The exterior retrofit system is designed to catch the building in the event of an earthquake. If the primary structure fails, the steel columns, which are not otherwise structurally loaded, will take over and keep the building from collapsing. These columns sit below the cantilevered galleries and atop new foundation work that includes a series of 3-foot to 3-foot 6-inch piers embedded to depths of up to 60 feet and capped together at grade. The interior system consists of new steel columns that brace the building in vulnerable areas and carry the loads all the way to the foundation. At the perimeter of the galleries, steel trusses tie the building together across the skylights to create continuous diaphragms. Overall, the strategy is an attempt to protect the building against collapse, but it does not incorporate any lateral interior bracing, tree wall strengthening, or tying together of the discrete gallery wings. Due to these deficiencies, the Pacific Film Archive, which can accommodate a relatively high concentration of people at a given time, chose not to reoccupy the building.

Though the intervention was minimal, a series of obstacles had to be overcome during the construction in 2001. Since the museum operates as part of a campus community, many scheduling considerations had to be addressed. Furthermore, a great deal of earth and steel had to be maneuvered in a very tight space. The piers supporting the exterior columns were deep and it was difficult to maneuver the reinforcement into the holes without damaging the cantilevered galleries above. Some reinforcement inside the existing concrete had collapsed, forcing last-minute changes in the connections of the exterior columns to the cantilevered walls.

The museum itself presented unique requirements. The outdoor area requiring excavation had large, heavy sculptures that were relocated during construction and a vibration specialist was needed to protect the collection. These unique considerations illustrate the importance of cooperation, communication, and coordination between the university representatives, structural engineers, contractors, and museum representatives who were working to improve the museum's usability.

Hearst Field Annex / Pacific Film Archive Theater

ARCHITECT:	GEZ ARCHITECTS ENGINEERS
ENGINEER:	GEZ ARCHITECTS ENGINEERS
DATE:	1999
SIZE:	37,100 SQ. FT.

ABOVE:
Exterior of the Pacific Film Archive and Hearst Field Annex. The Hearst Field Annex is used as temporary surge space for occupants of various campus buildings during seismic retrofits. The PFA was moved out of the museum to this location.

Barrows Hall

ARCHITECT:	ALECK L. WILSON AND ASSOCIATES
ENGINEER:	PAQUETTE AND MAURER
DATE:	1964
SIZE:	197,000 SQ. FT.
RETROFIT ARCHITECT:	HANSEN/MURAKAMI/ESHIMA
RETROFIT ENGINEER:	DEGENKOLB ENGINEERS
DATE COMPLETED:	2001

ABOVE:
Barrows Hall after retrofit.
Photo: Liz McBee

ABOVE:
Barrows Hall before retrofit. Photo by Steven Brooks.

Completed in 1964, Barrows Hall, an eight-story reinforced concrete building, was designed at a time when the campus architect, William Wurster championed a plan to erect high-rise buildings on the Berkeley campus to maximize open areas, while providing necessary space for an expanding university. The architects of Barrows Hall, Aleck L. Wilson and Associates, designed the building according to the aesthetics of the time with "piloti," or columns, popularized by Le Corbusier. The idea was to lessen the mass of the building on its ground floor, giving the impression that the superstructure was floating. The ground floor entrances at the east and west ends of the building were as generous as possible. They opened onto a wide interior corridor which led through the building from the east to the west entrance, and a courtyard to the north. The program called for an upper-story hall and the architects tried to lighten the roof structure above it. They were motivated to make their building as transparent as possible because it was the first high rise on campus and they knew it would obscure the view of the campanile from the south. While the architects succeeded in creating airy circulation spaces and a rooftop auditorium with a deep, continuous balcony and exquisite views, many of the offices and classrooms in the building were cramped and dark. Originally built to house the Business School, today Barrows Hall is the home of multiple departments, faculty, administrative offices, and classrooms.

In 1978, H. J. Degenkolb and Associates conducted the first seismic safety evaluation of the Berkeley campus buildings according to the 1975 rating system. Evaluations were made by analyzing the drawings and inspecting the exterior of the building. According to this preliminary survey, Barrows Hall rated Fair. Ten years later, in 1989, Stephen A. Martin, a professor in the Civil Engineering Department at Berkeley, and a member of the campus Seismic Review Committee, by chance walked through the building. He was alarmed by what he saw. In his judgment, Barrows Hall would likely suffer local structural and non-structural damage resulting in life-safety risks. He recommended that the Seismic Review Committee reevaluate the seismic safety of the building, but it was not until 1997, when funds became available, that Barrows Hall received a second evaluation. The building was then given a Poor rating, confirming Martin's judgment.

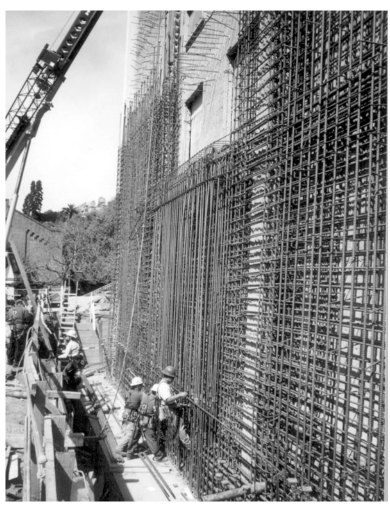
The seismic retrofit of Barrows Hall was completed by the architecture firm of Hansen/Murakami/Eshima and the engineering firm of Degenkolb Engineers. Several retrofit schemes were proposed by the design team, including adding buttresses, adding shear walls inside the building, and jacketing both ends of Barrows Hall. After much discussion, the scheme to jacket both ends of the building was selected. The jacketing scheme would increase the strength and stiffness of the building by adding shear walls at the ends of the building. These shear walls would be tied to the building and to the foundation using drag struts (or diaphram collectors) and boundary reinforcements. The jacketing scheme necessitated removing some windows on the east and west sides.

BELOW:
Rendering showing new jacketing scheme on east and west sides of Barrows Hall.

One of the main considerations driving the selection of the jacketing scheme was the need to keep Barrows Hall open during the construction process. The retrofit of Barrows was scheduled to begin in July of 2000 and to end in July of 2002. At the time, the university was already engaged in several retrofit projects and there was not enough surge space to accommodate the faculty, staff, and students that occupied Barrows Hall.

The retrofit required disruptive construction work, such as chipping and drilling the concrete walls in order to connect the new walls to the original structure. This work was originally scheduled during summer break to avoid disrupting the occupants, but the schedule was difficult to maintain when a number of the original contractors did not fulfill bidding regulations set by the state, thus requiring that the project be rebid. Because construction was delayed, chipping and drilling the concrete took place during the fall semester. Loud construction work was scheduled from 3 p.m.–10 p.m., but limiting noise within these time constraints proved to be quite difficult.

The Barrows Hall Seismic Safety Correction Program Committee continued to be a part of the project team, meeting every two weeks to address occupant issues and complaints. However, Barrows Hall is home to 13–15 different small departments, which made it difficult to disseminate information to all occupants.



ABOVE AND RIGHT:
View of installation of rebar for new shearwalls.

ABOVE:
New north entrance to Barrows Hall.
Photo by Liz McBee

Additionally, for much of the construction period, no point person was assigned to act on behalf of the occupants, to field their complaints and respond to issues as they arose. Based on the Barrows Hall experience, campus staff and faculty have advocated that retrofit work should not be undertaken with building occupants in place.

The Barrows Hall seismic retrofit project highlighted the importance of establishing communication networks to coordinate the exchange of information between contractors, building inhabitants, and neighbors. Before the retrofit was complete, some measures were implemented to deal with the problems, including noise monitoring and the distribution of frequent information updates. Additionally, a noise shelter was set up in a basement computer room as a retreat for occupants. Subsequent projects on the Berkeley campus benefited from the lessons learned during the Barrows Hall seismic retrofit. In later projects, e-mail lists and project websites were set up to ensure the timely and comprehensive exchange of information.

The retrofit of Barrows Hall substantially altered the appearance of the building. Despite the elimination of office windows and the sacrifice of transparency on the first story, many consider the retrofitted building to be more aesthetically appealing than the original. Certainly the new jacketing that buttresses each end adds depth to the exterior of the building, allowing light and shadow to animate the facade. Although emergency access was maintained on the east and west ends, a new entrance on the north side provides a pedestrian front door to the campus.

Jane K. Sather Tower

ARCHITECT:	JOHN GALEN HOWARD
DATE:	1914
SIZE:	11,680 SQ. FT.
RETROFIT ENGINEER:	FORELL/ELSESSER ENGINEERS (study only)
STUDY COMPLETED:	1997

South Hall

ARCHITECT:	DAVID FARQUHARSON
DATE:	1873
SIZE:	30,401 SQ. FT.
RETROFIT ARCHITECT:	EHDD ARCHITECTURE
RETROFIT ENGINEER:	RUTHERFORD AND CHEKENE
DATE COMPLETED:	1988

ABOVE:
View of the east side of South Hall.

ABOVE:
Side view of South Hall.

Completed in 1872 and designed by David Farquharson, South Hall was the university's first building on the site of the Berkeley campus. Work on South Hall began two years after the 1868 magnitude 7.0 earthquake on the Hayward fault. Because of the considerable damage caused by this earthquake and because of the proximity of the campus to the fault, the Regents of the University had committed to an earthquake-safe building and campus.

At that time, having learned from previous earthquakes, the architecture and engineering communities had some understanding of seismic-resistant design. They were aware that buildings with strong ties and connections behaved as a unit and performed better in earthquakes. They were also aware that low wood buildings, due to the ductility of wood, performed quite well in seismic events. Stiff brick and stone buildings, however, were more likely to crack and crumble rather than flex when subjected to the lateral force of an earthquake. Since wood was seen to be more earthquake-resistant than either stone or brick, the regents early in the planning phase decided that South Hall should be built of wood. This decision was highly criticized in the press. Building materials such as iron and brick were more enduring and were thought to embody ideas of progress and the future more appropriately for Berkeley's first building. Eventually, the regents hired Farquharson and accepted his design of an iron-reinforced brick building.

Farquharson employed many different strategies in his design of South Hall to make the building earthquake resistant. Within the brickwork of South Hall, Farquharson wove a network of wrought iron reinforcement to tie the building togeth-

ABOVE:
View of South Hall entrance.

er. Heavy iron girders supported the floors, and strong brickwork and mortar, diagonal sheathing, iron tie bars, anchors, and columns were all used to strengthen the building. The iron rods extended through the building and are visible on the exterior, attached to iron pilasters by decorative bolts. Farquharson intended the iron to provide the elasticity and support for the building, while the brick and mortar provided the bulk and lateral rigidity.

One hundred years after it was built, when engineers were conducting a seismic analysis of the buildings on the Berkeley campus, South Hall was thought to be dangerous because of its brick construction. Studies conducted in 1975 and 1982 revealed that although the extensive iron reinforcing ran through the entire building, all masonry buildings were a potential hazard if not compliant with modern code. Between 1986 and 1988 the engineering firm of Rutherford and Chekene and the architectural firm of Esherick, Homsey, Dodge, and Davis were hired to complete a retrofit.

During the retrofit, the design team found that the roofs of the north and south wings were poorly built and during an earthquake would not act as diaphragms as Farquharson had intended. Due to the high ceilings, the walls were too thin to resist buckling. Additionally, the chimneys were likely to fall, and because they also compromised the continuity of the walls, further limited their resistance to shear force. It was found that even the bond iron would be inefficient once it reached its yield strength and was therefore unlikely to hold the bricks together during a major seismic event.

To strengthen South Hall, concrete ring beams were installed around the perimeter of the north and south roofs to secure the tops of the walls. New concrete and steel floors in the central cor-

ABOVE:
View of South Hall.

ridor were added to tie the central section of the building to the new concrete walls that were installed around the north and south wings. Where the chimneys compromised the continuity of the walls, the interior walls of the chimneys were cut away and replaced with a reinforcing framework. The interior walls were then sprayed with concrete to further reinforce them. In order to prevent the central walls from buckling, reinforcement bars were inserted inside the 60-foot walls, which required drilling holes in the walls that extended vertically from the roof to the foundation. Despite the deficiencies of the original building and the necessary reinforcements added during the retrofit, Farquharson's design was exceptional for its time. Located prominently in the classical core of the central campus, South Hall is listed on the National Register of Historic Places and is a City of Berkeley landmark. The seismic retrofit was completed in a period when structural work replaced many of the historic interior finishes. Today a seismic solution would pay greater attention to preservation of materials and finishes.

LeConte Hall

ARCHITECT:	JOHN GALEN HOWARD
DATE:	1924
SIZE:	148,032 SQ. FT.
RETROFIT ARCHITECT:	MURAKAMI/NELSON
RETROFIT ENGINEER:	DEGENKOLB ENGINEERS
DATE COMPLETED:	2005

ABOVE:
View of LeConte Hall.

Doe Library

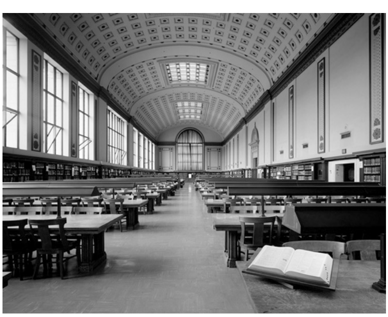
ARCHITECT:	JOHN GALEN HOWARD
DATE:	1911 and 1917
SIZE:	471,159 SQ. FT.
RETROFIT ARCHITECT:	EHDD ARCHITECTURE (phase I)
	HANSEN/MURAKAMI/ESHIMA (phases II and III)
	RADCLIFFE (phase IV)
RETROFIT ENGINEER:	RUTHERFORD AND CHEKENE (phase I)
	DEGENKOLB ENGINEERS (phases II and III)
DATE COMPLETED:	1997 (phases I, II and III)

ABOVE:
View of Doe Library.

The year after the 1906 earthquake, construction began on the main library complex for the University of California. Doe Library, begun in 1907 and expanded in 1915, composed the academic center of the university. The main library complex now consists of Doe Library, Doe Annex (Bancroft Library), and Moffitt Library. Because Doe Library was designed and built in stages, it has recorded many of the changes in attitudes, knowledge, and approaches to seismic design and can be seen as a narrative of the history of seismic design strategies.

Designed by John Galen Howard, Doe Library consists of a concrete slab, a steel frame with concrete infill, steel-cored concrete columns, granite cladding and tile roofing. Five years after it was built, efforts were begun to strengthen the building. During the 1915 expansion, the steel-cored concrete columns were reinforced with iron bars and an additional concrete covering. Additionally, the extant reinforcement in the concrete slab floors was extended into the new slab of the expansion. During the mid-1920s, when a major addition to the stacks was under way, contractors used electric arc welding rather than bolting to increase the rigidity of framework connections.

In 1987, when Degenkolb Engineers performed a seismic evaluation of the main library complex, Doe Library was given a Poor rating and the stack structure was rated Very Poor. Given the complexity of the project, the Doe Library retrofit would demand a multi-phased and multi-faceted strategy. Begun in 1992, construction for the retro-



ABOVE:
View of Doe Library.
LEFT:
View of North Reading Room in Doe Library.

ABOVE:
View of Doe Library Annex. Photo courtesy of UC Berkeley Capital Projects.

fit was a process in which many techniques were used to address varying concerns and included relocating the core as well as seismic strengthening. The architecture firm Esherick, Homsey, Dodge and Davis (EHDD), proposed eleven possible options for this undertaking. The scheme that was selected added new underground stacks to the north and east of the existing Doe Library and provided a connection to the Moffitt Undergraduate Library. Four major structural interventions were deemed necessary for the Doe Library retrofit. New shear walls were constructed in the vacated core, floor diaphragms were strengthened, vertical supports (columns, girders, and beams) were strengthened to increase floor-load capacities, and the North Reading Room and Subject Catalog Room were strengthened in such a way as to maintain extant architectural details.

The retrofit of the main library complex was completed in three phases and involved a number of different engineering and architecture firms. Rutherford and Chekene served as engineers for the initial phases of construction and Degenkolb engineered subsequent phases. The architecture firms involved were EHDD for the first phase, Hansen/Murakami/Eshima for the second and third phases, and Radcliffe for the not yet completed fourth

phase. Step I included the seismic upgrade of Moffitt Library and the construction of new stacks. Step II involved the demolition of the Doe Library core stacks and the construction of shear walls surrounding the core. The metal free-standing stacks of Doe Library were dismantled from below and pulled out of the building through a new loading dock at the basement level. Created specifically for the retrofit, the loading dock allowed construction to take place while the library was in use.

During Step II, the columns were also upgraded and the perimeter walls of the building were tied to the core shear wall system. Three sky trusses were mounted to the new core in Step III. These trusses were designed to collect all the loads from the facade and tie it back to the core. The North Reading Room is listed in the National Register of Historic Places and required strengthening while maintaining its aesthetic integrity. Without removing any skylights or windows, the room's shear walls were strengthened and sky trusses were added to relieve roof loads. The Doe Annex (Bancroft Library) retrofit is scheduled as Step IV, to start construction in early 2006. The retrofit of Doe Library differed from the retrofits of many other campus buildings, such as University Hall, in that the visibility of the interventions was not desired because of the library's historical significance.

ABOVE:
Installation of shear walls.
BELOW:
Bracing during construction.

Moffitt Library

ARCHITECT:	JOHN CARL WARNECKE AND ASSOCIATES
ENGINEER	T. Y. LIN, KULKA, YANG AND ASSOCIATES
DATE:	1967
SIZE:	132,000 SQ. FT.
RETROFIT ARCHITECT:	EHDD ARCHITECTURE
RETROFIT ENGINEER:	RUTHERFORD AND CHEKENE
DATE COMPLETED:	1993

ABOVE:
View of Moffitt Library. Photo courtesy of UC Berkeley Capital Projects.

McCone Hall

ARCHITECT:	WARNECKE AND WARNECKE
DATE:	1961
SIZE:	115,000 SQ. FT.
RETROFIT ARCHITECT:	GORDON H. CHONG AND ASSOCIATES
RETROFIT ENGINEER:	DEGENKOLB ENGINEERS
DATE COMPLETED:	1999

ABOVE:
View of McCone Hall with Memorial Glade in foreground. Photo courtesy of UC Berkeley Capital Projects.

Part Three
North and West Campus

Barker Hall

Goldman School of Public Policy

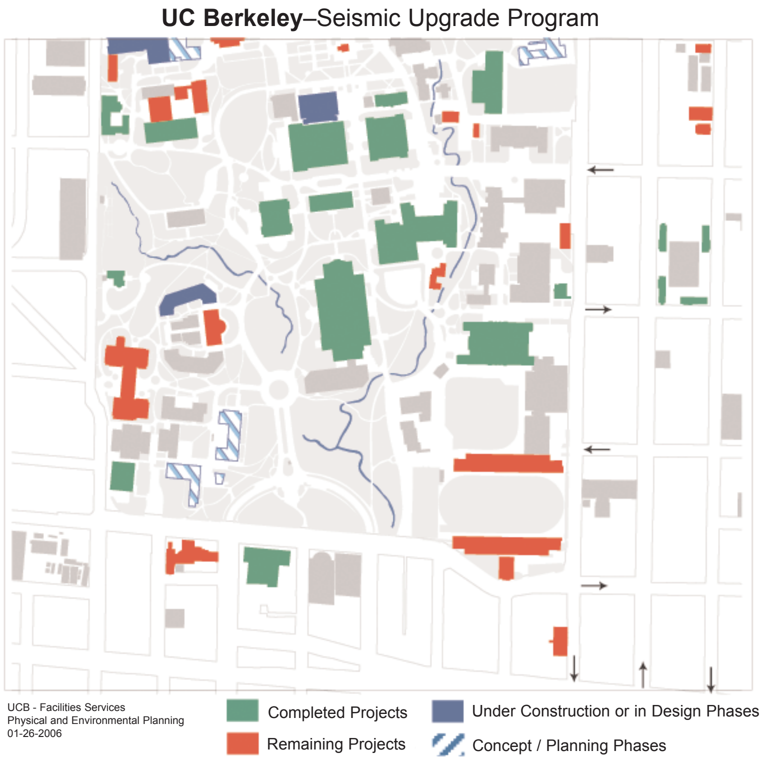
North Gate Hall

Martin Luther King, Jr. Student Union

Residence Hall, Unit 3

The Dance Facility

University Hall


UC Berkeley–Seismic Upgrade Program
UCB - Facilities Services
Physical and Environmental Planning
01-26-2006
Completed Projects
Remaining Projects
Under Construction or in Design Phases
Concept / Planning Phases

Barker Hall

ARCHITECT:	WURSTER, BERNARDI AND EMMONS
DATE:	1964
SIZE:	91,144 SQ. FT.
RETROFIT ARCHITECT:	ANSHEN AND ALLEN
RETROFIT ENGINEER:	FORELL/ELSESSER ENGINEERS
DATE COMPLETED:	2002

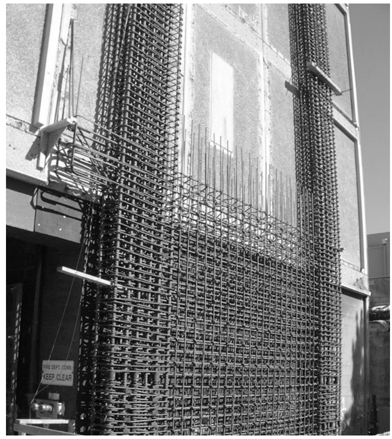
ABOVE:
View of Barker Hall after retrofit.

Barker Hall houses the Molecular and Cell Biology departments. Built in 1959 and located on the northwest side of the campus, at the corner of Oxford and Hearst, Barker Hall is a seven-story concrete shear wall building consisting of exterior panels of precast concrete connected to a cast-in-place concrete frame. At the time it was constructed, Barker Hall was thought to have adequate shear wall capacity to resist earthquakes. However, during the 1989 Loma Prieta earthquake, the building was moderately damaged and, in the 1997 campus-wide seismic evaluations, was given a Poor rating.

The engineering firm of Forell/Elsesser was hired to evaluate the existing structure and to propose several possible retrofit schemes. The structural system of Barker Hall consists of shear walls and a reinforced concrete pan joist and column structural system. Individual spread footings bear the weight of the columns, while a continuous spread footing around the perimeter of the building bears the weight of the basement wall. The soil condition is dense and sandy clay, which has a relatively high load-bearing capacity. The core elements that would normally resist lateral force were found to be relatively weak in a number of ways. The precast/pretensioned concrete panel cladding system was found to be not only brittle but insufficient to resist the lateral load due to the pattern of the window openings, which created a random shear wall system. In addition, the tops and sides of the panels were connected to the perimeter beams and columns by dowels, but the bottoms of the

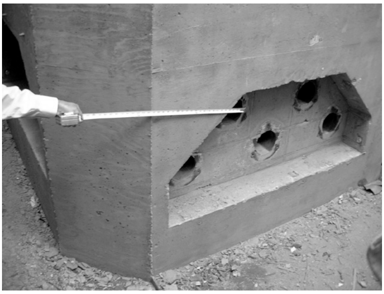
ABOVE:
Barker Hall before retrofit.
LEFT:
Installation of new exterior shear walls.

panels were not connected at all. Shims, instead of dowels, were found between the bottoms of the panels and the beams. Additionally, the perimeter columns did not contain closed ties and the existing frame was found to be inadequate to resist seismic forces.



During the beginning phases of their analysis, the engineers considered many retrofit approaches, including adding either interior or exterior shear walls and collectors, constructing exterior buttress towers and interior collectors, and building supplemental columns at the perimeter. The perimeter column scheme was selected because it would allow at least partial occupation during the retrofit. The engineers,

ABOVE:
Rebar for exterior shear walls.
BELOW:
Rebar for foundation.



ABOVE:
Detail of construction.

Forell/Elsesser, and the project architects, Anshen and Allen, drew up the final plan to add eight exterior shear walls (two per side) and collectors, and drilled pier foundations. Later the foundation was changed to a continuous post-tensioned concrete perimeter foundation. The new foundation was constructed 10 feet below the old perimeter foundation. It is a post-tensioned concrete belt beam, 6 feet wide and 11 feet deep. The entire building had to be underpinned because of the close-in construction.

An unusual feature of the project is the use of fly ash, a "green" alternative to conventional concrete. Fly ash is a relatively new and popular ingredient in a concrete, which increases its strength and performance. Because fly ash is a by-product of coal burning, recycling this waste product of the energy industry is environmentally efficient. A fly ash mix was used for all the concrete used in the upgrade of Barker Hall including all exposed walls.

Basic structural upgrading of the reinforced concrete shear wall system was achieved with exterior cladding of glass-fiber reinforced concrete and metal panels. The retrofit construction began in 2000 and was completed in 2003. While the upgrade would meet the expectations of the university for the building to conform to life-safety requirements, an earthquake could damage the building's concrete panel enclosure.

Goldman School of Public Policy

ARCHITECT:	ERNEST COXHEAD
DATE:	1893
SIZE:	12,349 SQ. FT.
NEW ADDITION ARCHITECT:	SMITH GROUP
NEW ADDITION ENGINEER:	GFDS ENGINEERING
RETROFIT ARCHITECT:	ARCHITECTURAL RESOURCES GROUP
DATE COMPLETED:	1999 (new addition)
	2003 (retrofit)

North Gate Hall

ARCHITECT:	JOHN GALEN HOWARD
DATE:	1912
SIZE:	23,748 SQ. FT.
RETROFIT ARCHITECT:	STOLLER KNOERR ARCHITECTS
RETROFIT ENGINEER:	STRUCTUS
DATE COMPLETED:	1993

Martin Luther King Jr. Student Union

ARCHITECT:	HARDISON AND DE MARS
ENGINEER:	PREGNOFF AND METHEU
DATE:	1961
SIZE:	115,500 SQ. FT.
RETROFIT ENGINEER:	FORELL/ELSESSER ENGINEERS (study only)

ABOVE:
View of Martin Luther King Jr. Student Union from upper Sproul Plaza.

Residence Hall, Unit 3

ARCHITECT:	JOHN CARL WARNECKE AND ASSOCIATES
ENGINEER:	ISADORE THOMPSON
DATE:	1964
SIZE:	175,016 SQ. FT.
RETROFIT ARCHITECT:	GORDON H. CHONG AND ASSOCIATES
RETROFIT ENGINEER:	DEGENKOLB ENGINEERS
DATE COMPLETED:	1988

ABOVE:
View of Residence Hall, Unit 3 after retrofit. Photo courtesy of UC Berkeley Capital Projects.

The Dance Facility

ARCHITECT:	ALBERT C. SCHWEINFURTH
DATE:	1898
SIZE:	3,706 SQ. FT.
RETROFIT ARCHITECT:	MULLER AND CAULFIELD
RETROFIT ENGINEER:	INGRAHAM-DEJESSE ASSOCIATES
DATE COMPLETED:	1999

ABOVE:
View of the Dance Facility.

University Hall

ARCHITECT:	WELTON BECKETT AND ASSOCIATES
ENGINEER:	MURRAY ERICK ASSOCIATES
DATE:	1957
SIZE:	155,181 SQ. FT.
RETROFIT ARCHITECT:	HANSEN/MURAKAMI/ESHIMA
RETROFIT ENGINEER:	DEGENKOLB ENGINEERS
DATE COMPLETED:	1991

ABOVE:
View of the west and south sides of University Hall after retrofit.

Located in downtown Berkeley on the corner of Oxford and Addison streets, and buttressing the west end of campus, stands the seven-story tower of University Hall. The prominent exterior steel X-bracing provides a striking testimony of the university's seismic retrofit program. While these structural steel elements may show their purpose, they do not tell of the ten-year process that put them there.

The original architects, Welton Beckett and Associates, and the structural engineering firm of Murray Erick Associates designed University Hall in 1957. The building was made of a reinforced concrete frame and 7-foot-deep beams, clearly indicating that the original design team had seismic forces in mind. However, seismic codes were minimal in 1957, and even by 1978 a preliminary seismic survey performed by Degenkolb Engineers ranked University Hall among the least seismically resistant buildings on campus.

The seismic deficiency of the original University Hall design was primarily due to its deep beams and short, slender columns. The 8-inch by 7-foot-deep beams were huge compared to the 24-inch square columns. The stiff beams, together with the mass of the 4½-inch-thick concrete floors would easily take the

BELOW:
View of the east side of University Hall after retrofit.

ABOVE:
South entrance to University Hall displays soft story.

lateral forces of an earthquake and deliver them to the weaker columns. Without sufficient length over which to develop any flexural strength, these columns would then fail in shear.

Structural engineers found in University Hall an additional seismic deficiency called a "soft story." Lateral forces acting on a building during an earthquake accumulate as they travel from the top of the structure to the ground. Therefore, the base of the building must provide sufficient resistance to these accumulating loads. If the first story is too weak, it will collapse under the weight of the upper floors—hence the term "soft story." University Hall suggested this weakness because the first floor is recessed on the south, east, and north sides. The exterior walls of the tower do not extend down to the ground, but stop above the first floor, with columns extending to the ground.

Based on the report from Degenkolb Engineers, the university appealed to the state for $1.6 million in 1980 in order to conduct more refined studies. The state granted the university $590,000, but withheld further appropriations until complete rankings of all state buildings were received, not just those belonging to the UC system. Although the state building review was completed in 1981, it was not until after the California State Legislature enacted the California Earthquake Hazards Reduction Act of 1986 that seismic repair funds started trickling into all UC campuses. By 1988 the budget was finally in place to conduct further studies on University Hall and to assess strengthening options.

Degenkolb Engineers acted as structural engineers on the 1988 University Hall study and proposed three retrofit schemes to UC Berkeley's Seismic Review Committee. In the chosen scheme, steel X-frames were added to the exterior of the building, providing clear, visual articulation of the long-awaited seismic improvements. To prevent early column failure, the engineers also proposed connecting steel to either side of the concrete columns with epoxy-threaded rods. The scheme also included adding a horizontal truss member to the roof and installing reinforced concrete shear walls to the first floor to prevent soft-story failure.

In October of 1989, the Loma Prieta earthquake struck the Bay Area, leading to heightened public awareness regarding building safety. Newly appointed UC President Gardner declared seismic safety of the utmost importance and earmarked administration fees toward immediate seismic retrofit. These funds amounted to approximately $50 million. Berkeley officials quickly applied for money from these appropriations to push University Hall, next on the waiting list, toward design completion and construction.

Responding to UC Berkeley's urgency, the chosen design team, including the architectural firm of Hansen/Murakami/Eshima (HME) along with Degenkolb Engineers, rapidly produced construction documents and submitted complete drawings and specifications in just six months. While producing the construction documents, HME made considerable efforts to improve the aesthetics of the retrofit without reducing structural integrity. After some discussion with the engineers, they changed the asymmetrical bracing pattern along the longitudinal walls to a tapered down, symmetrical pattern, added a three-band relief pattern at the top of the first-floor columns, and added to the roof a short band of X's to complement and balance the structural X-bracing.

BELOW:
Detail of X-bracing.

Special aesthetic attention was given to the connections of the braced frames, since the connections would be visible on the exterior of the building. Because connections require considerable cutting, drilling, and welding, they frequently end up the messiest looking part of a steel structure. Two critical groups of connections existed in the retrofit system:

the brace intersection where six pieces came together (two beams and four braces) and the column-to-column connections where steel columns connected to concrete columns. At the column-to-column connections, engineers provided steel plates to which fabricators could fillet weld the steel columns on site. These steel plates were connected to the concrete columns by coring across the concrete column and inserting 4- or 5-inch pipes that were then welded to the plates. To make welding as simple as possible, 8-inch wide flange shapes were chosen for all beam, brace, and column sections.

The design allowed prefabrication of the braced frames, which was not only an economic solution, but also made for an efficient construction. The contractors prefabricated each frame assembly on an empty lot adjacent to University Hall. During construction, each frame was raised by crane above the roof and fit between the face of the building and the scaffolding. Construction of the structural retrofit took less than two years to complete. Today, University Hall houses the university's Financial Services and Human Resources departments as well as part of the School of Public Health. Situated near the heart of downtown Berkeley, University Hall announces its seismically sound design, serving as a symbol to UC Berkeley's students, employees and the community at large.

Appendix

The University of California Rating System

The UC Regents established a Seismic Safety Policy in 1975 that uses the performance ratings of Good, Fair, Poor, and Very Poor as defined below. These continue to serve as the backbone of the program.

A Good seismic performance rating would apply to buildings and other structures whose performance during a major seismic event is anticipated to result in structural and nonstructural damage and/or falling hazards that would not significantly jeopardize life. Buildings and other structures with a Good rating would represent an acceptable level of earthquake safety, such that funds need not be spent to improve their seismic resistance to gain greater life safety.

A Fair seismic performance rating would apply to buildings and other structures whose performance during a major seismic event is anticipated to result in structural and nonstructural damage and/or falling hazards that would represent low life hazards. Buildings and other structures with a Fair seismic rating would be given a low priority for expenditures to improve their seismic resistance and/or to reduce falling hazards so that the building could be reclassified as Good.

A Poor seismic performance rating would apply to buildings and other structures expected to sustain significant structural and nonstructural damage and/or result in falling hazards in a major seismic event, representing appreciable life hazards. Such buildings or structures either would be given a high priority for expenditures to improve seismic resistance and/or to reduce falling hazards so that the building could be reclassified as Good, or would be considered for other abatement programs, such as a reduction of occupancy.

A Very Poor seismic performance rating would apply to buildings and other structures whose performance during a major seismic event is anticipated to result in extensive structural and nonstructural damage, potential structural collapse, and/or falling hazards that would represent high life hazards. Such buildings or structures either would be given the highest priority for expenditures to improve their seismic resistance and/or to reduce falling hazards so that the building could be reclassified as Good, or would be considered for other abatement programs, such as reduction of occupancy.

For a glossary of seismic design terminology, see the *FEMA Earthquake Hazard Mitigation Handbook* at:
http://www.conservationtech.com/FEMA-WEB/FEMA-subweb-EQ/